Project Title:

Design and assembly of fast and light-weight barrel and forward tracking prototype systems for an EIC

Progress report (FY13) and Proposal (FY14)

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Proposed Project Period:	October 01, 2013 - September 30, 2014
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Contents

1 Introduction

The detector specifications for the EIC science case has been discussed during a long INT workshop series in fall 2010 [1]. The science case has been documented in a recently announced White paper report [2]. The BNL and Jefferson Lab teams have come up with a preliminary detector design, including details on several tracking systems needed to achieve the proposed physics program. A side view of an EIC detector concept is shown in Figure 1. This proposal report focuses on two distinct tracking regions:

- Barrel tracking system based on MicroMegas detectors manufactured as cylindrical shell elements and
- Forward tracking system based on triple-GEM detectors manufactured as planar segments.

The barrel and forward tracking systems are shown as grey hashed areas in the EIC detector concept labeled 'Tracking' in Figure 1.

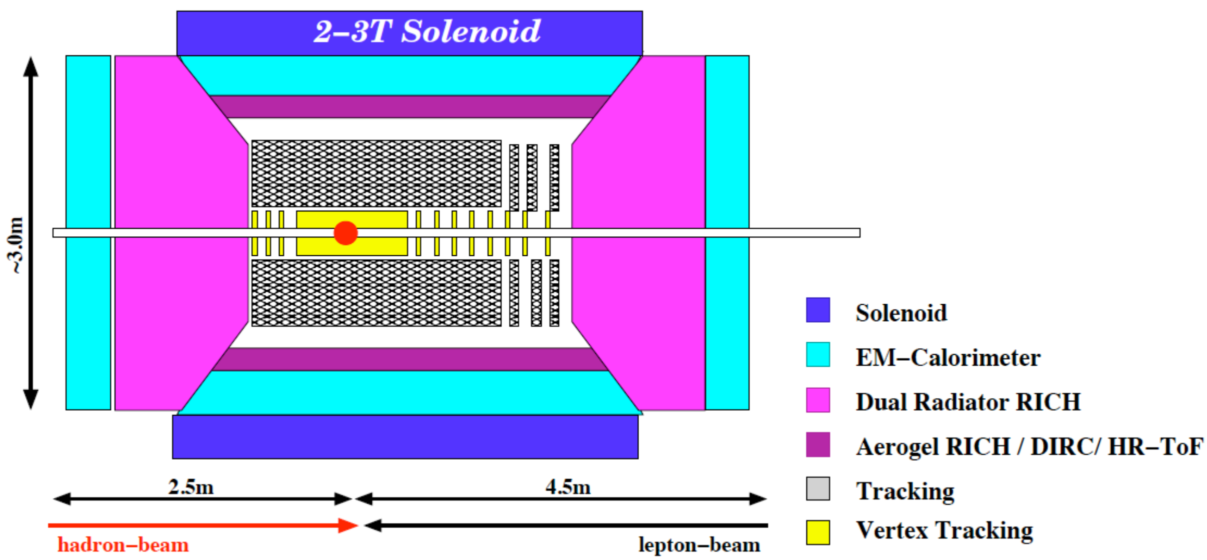


Figure 1: *Side view of an EIC detector concept.*

Figure 2 shows a 3D view of the barrel and forward tracking region. The report provides an overview of progress made in FY13 and the R&D needed in FY14 both in the barrel and forward/backward region. The R&D effort focuses on the following areas:

- Design and assembly of large cylindrical MicroMegas detector elements and planar triple-GEM detectors
- Test and characterization of MicroMegas and triple-GEM prototype detectors

- Design and test of a new chip readout system employing the CLAS12 'DREAM' chip development
- Utilization of light-weight materials
- Development and commercial fabrication of various critical detector elements
- European/US collaborative effort on EIC detector development (CEA Saclay, MIT and Temple University)

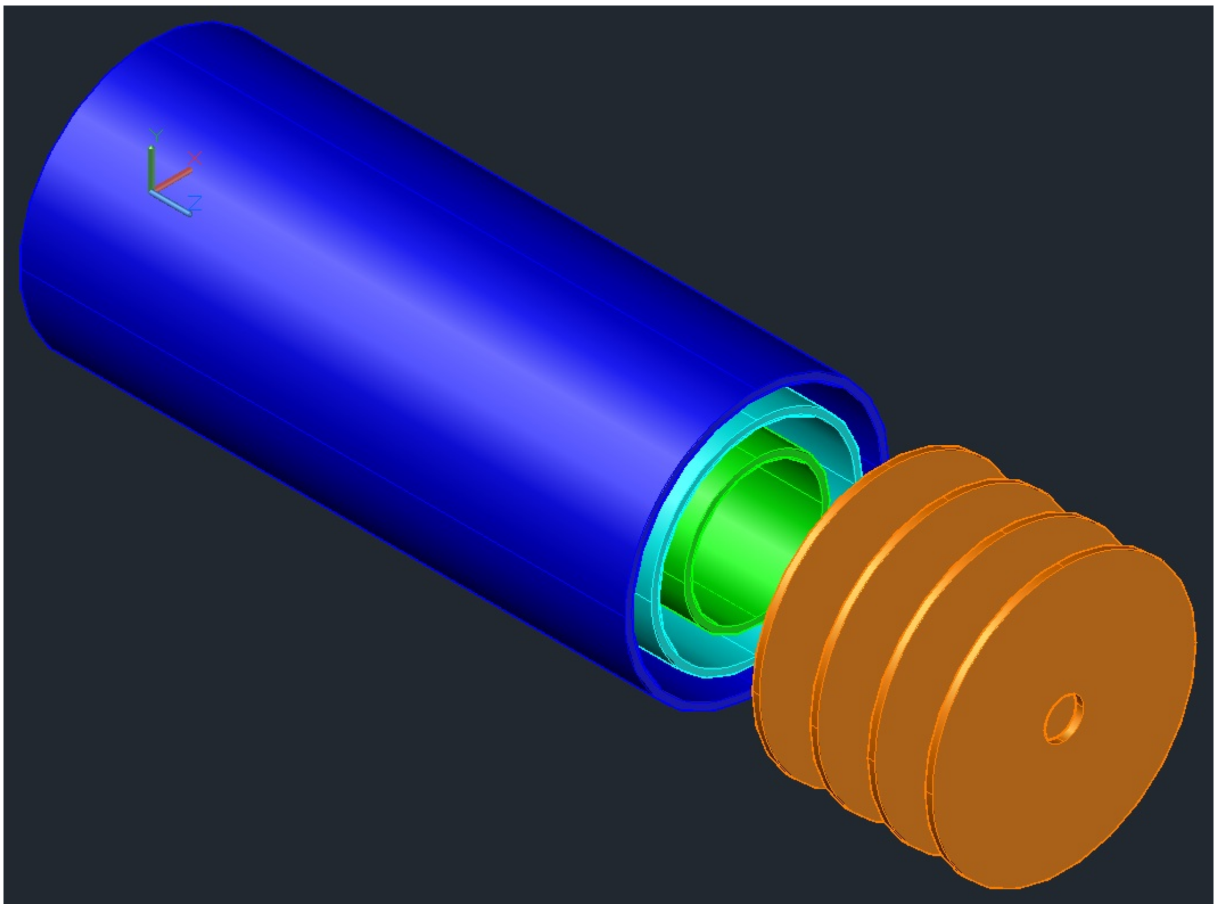


Figure 2: *Illustration of a barrel and forward tracking system for an EIC detector.*

It should be emphasized that it is in particular the chip readout which provides a common R&D effort for both the MicroMegas and the triple-GEM detector systems. The beginning R&D program in FY13 profited enormously from funds provided by a DOE EIC R&D grant of $\$150,000$ which allowed to accomplish the following:

- Forward GEM Tracking detector development
  - Appointment of Dr. Maxence Vandenbroucke at Temple University on October 01, 2012
  - Setup of two labs, a detector and dedicated clean room, in the current Department of Physics at Temple University

  - Characterization of GEM foils in terms of leakage current and optical uniformity
  - Assembly of small ($10 \times 10\,\mathrm{cm}^2$) triple-GEM test detectors
  - Setup of cosmic-ray test stand and ^{55}Fe source scanner
  - Setup of DAQ and HV system
  - Mechanical design studies on large triple-GEM detector segment and support structure
  - Commercialization of large GEM foil production using single-mask manufacturing techniques

- Barrel MicroMegas tracking detector development
  - Assembly of two CLAS12 MicroMegas detectors
  - Test of two CLAS12 MicroMegas detectors in cosmic-ray test stand
  - Successful test of light-weight, low capacitance flex cables
  - Test of first DREAM chip production version v0

The College of Science and Technology at Temple University provides new, outstanding educational and research opportunities with a strong emphasis on minority students and undergraduate students. Professor Bernd Surrow and Dr. Maxence Vandenbroucke managed to attract several outstanding students, both foreign and domestic students. More than 50% are considered minority students. The College of Science and Technology established an Undergraduate Research Program (URP) to encourage undergraduate student participation in research. Students who are selected to participate will work with a faculty sponsor to perform research in the faculty member's lab. A maximum of two undergraduate students can be supported per semester by the URP program. URP students will register for a research course within their major of study. Students are encouraged to participate in conferences, author papers or to showcase their research work in the department or at the URP Research Symposium. This program is similar in spirit to the MIT Undergraduate Research Opportunity Program (UROP). The DOE EIC R&D effort at Temple University has provided a huge attraction for students to join the Temple University group.

The progress report (FY13) and proposal (FY14) will start with an overview of achievements in chapter 2 ('Progress report - FY13') followed by a detailed discussion of R&D plans in chapter 3 ('Proposal - FY14'). Chapter 4 ('Budget and Schedule') will provide an overview of the allocation of funds in FY13 along with a discussion of R&D funding needs in FY14 and the overall schedule.

2 Progress report - FY13

2.1 Forward GEM tracking detector development

Overview The progress on the Forward GEM tracking activities was driven by the hire of Dr. Maxence Vandenbroucke as a Postdoctoral Research Fellow on October 01, 2012 along with five undergraduate students at Temple University. Two additional undergraduate students focused their effort primarily on a beginning GEANT4 simulation of an EIC tracking system. Almost all test setups are by now in place in the current Department of Physics at Temple University utilizing an existing dedicated clean room along with a large detector lab. Dr. Maxence Vandenbroucke will remain at Temple University until October 30, 2013 and then move for about six months to CEA Saclay (France) focusing on the MicroMegas R&D effort. The MIT effort under the leadership of Dr. Doug Hasell is mainly geared towards the development of spacer grids for large area triple-GEM detectors. In addition, the engineering expertise at MIT Bates with Ben Buck (Electrical engineer) and Jason Bessuille (Mechanical engineer) was and will be instrumental for the layout of both the chip readout system and the mechanical design. Each area of progress as introduced in Chapter 1 will be highlighted below in more detail. All goals have been achieved apart from the beginning process to manufacture large single-mask produced GEM foils at CERN. This step requires to finalize the mechanical design which will be discussed below and in Chapter 3.

Laboratory setup at Temple University The College of Science and Technology provided dedicated lab space for the development of micro-pattern detectors focusing in particular on triple-GEM detectors. The facilities in the current Department of Physics provided are:

- Clean Room (~ 500 sq.ft.), Class $1,000$: Handling of bare GEM foils including leakage current measurements and triple-GEM detector assembly / Microscope inspection of GEM foils
- Detector lab (~ 1000 sq.ft.): Testing of triple-GEM detectors including cosmic-ray testing, ^{55}Fe-source testing and CCD camera scan testing. A dedicated DAQ system based on the STAR FGT DAQ system is in preparation.

The maintenance of the clean room is provided by the College of Science and Technology.

The current Department of Physics provides a well-equipped electronics and machine shop. One head engineer (Ed Kaczanowics) including a mechanical technician (Matt McCormick) and electronics technician (Richard Harris) work as a team for research needs of the physics faculty. The technical team provided excellent support setting up a new lab. The electronics and machine shop along with the technical staff will be also available once the physics department is located in the new building housing the Science Education and Research Center.

Figure 3 shows the detector lab layout in the current Department of Physics at Temple University focusing on various setups of the triple-GEM R&D effort.

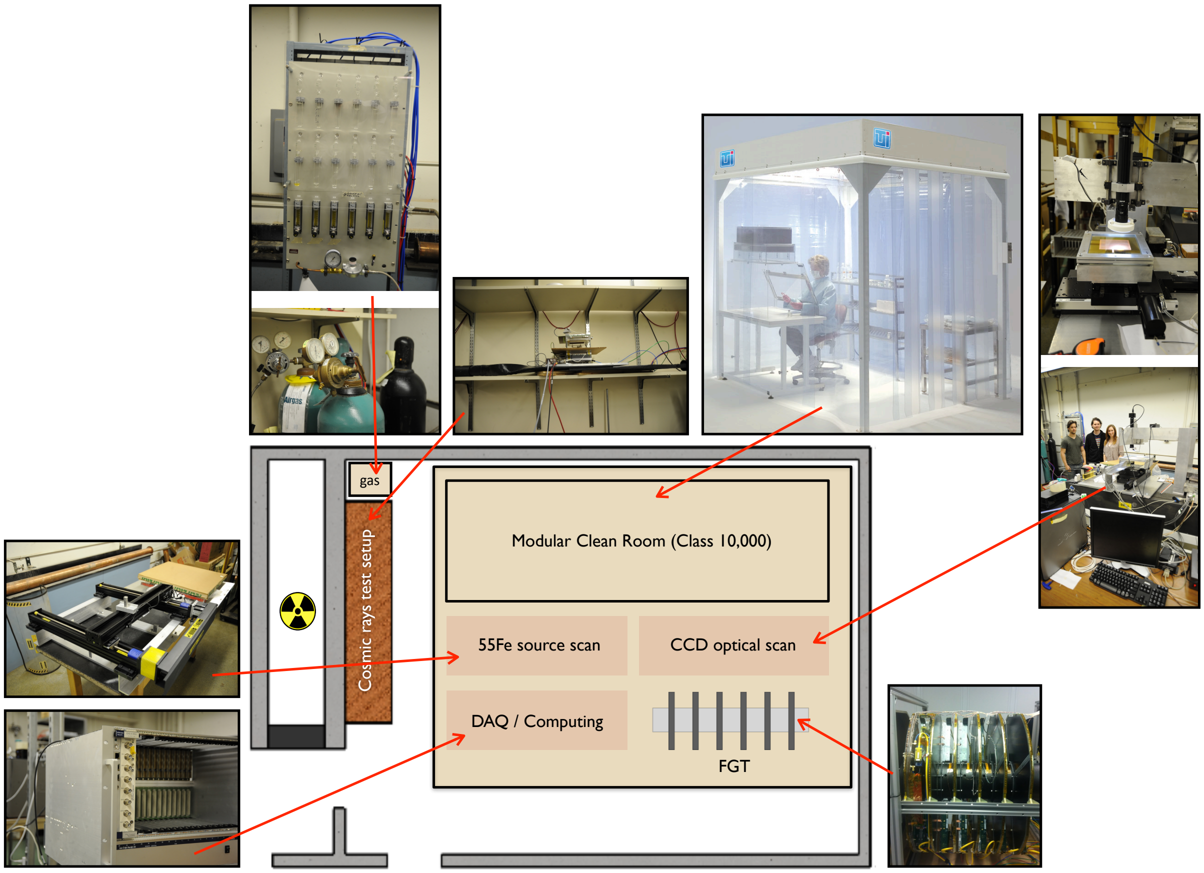


Figure 3: *Detector lab layout in the current Department of Physics at Temple University focusing on various test setups.*

Figure 4 shows an overview of the new Science Education and Research Center, which will be at the same time the home of the new physics department. Professor Bernd Surrow played an integral part in the layout of a dedicated, large Class 1,000 clean room facility (1,800 sq.ft.) shown in Figure 4 (b). The maintenance of the clean room is fully covered by the College of Science and Technology. The main focus of the research activities are large micro-pattern detector development and silicon sensor handling, testing and assembly. The clean room facility provided for Professor Bernd Surrow is connected to a smaller Class 100 clean room focusing on material science. It has been agreed that Professor Bernd Surrow could use this clean room as well if the need arises, e.g. for novel silicon sensor development for a future Electron-Ion Collider facility. In addition to the Class 1,000 clean room facility, Professor Bernd Surrow participated in the layout of a dedicated detector lab (800 sq.ft.). Both labs are fully equipped with basic lab furniture, network and power connections in addition to gas services such as nitrogen gas, dry-air and pre-mixed ArCO2 gas. Special marble tables for detector testing and assembly are provided in both labs. It is expected that the Department of Physics at Temple University moves to the new building inside the new Science Education and Research Center in summer 2014.

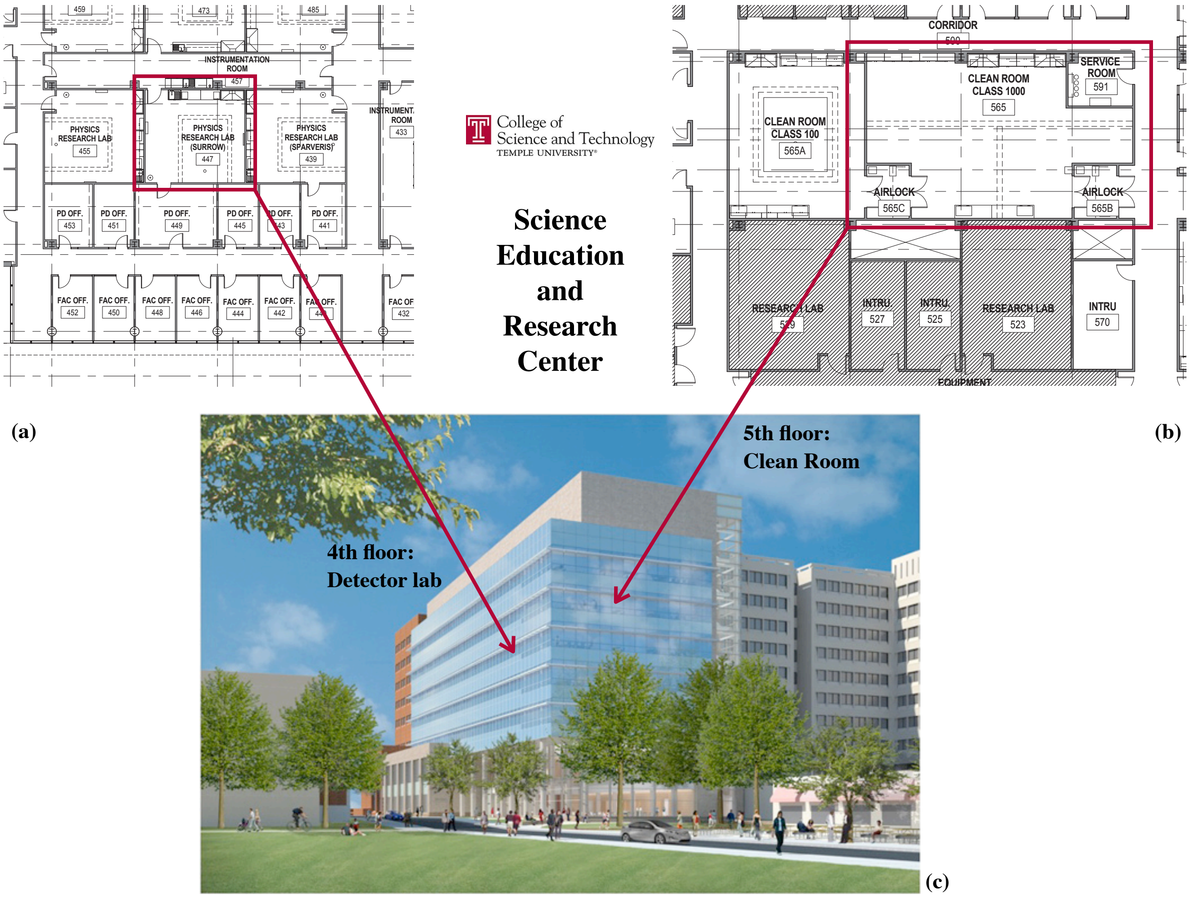


Figure 4: *Overview of the Science Education and Research Center (c) together with the layout of the new detector lab (a) and Clean Room facility (b).*

GEM foil characterization - Leakage current The first type of characterizations performed on a GEM foil are electrical tests. As shown in Figure 5, a GEM foil is first placed in a gas tight plexiglas enclosure used to provide a safe and dry nitrogen environment. The leakage current is then measured between the unsegmented side and segmented, i.e. sector side for a GEM foil as a potential difference is applied up to 600 V. With increasing applied voltage, the current is monitored to avoid destructive discharge. The typical leakage current is a few nA. Figure 6 shows the results of such a measurement where one can see that the current increases with the applied voltage for the different sectors of a GEM foil, in this case a GEM foil from the STAR Forward GEM Tracker (FGT).

This setup has been installed in the cleanroom at Temple University where this measurement is performed in a clean environment by undergraduate students as shown in Figure 5. A full batch of foils has already been tested. This procedure is quite time consuming. It is therefore planned to automate the leakage current measurement in the future which will be relevant for larger foils with a larger number of sectors.

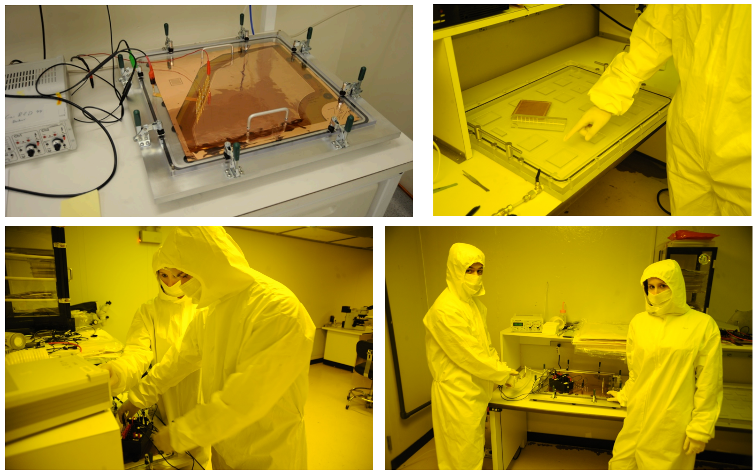


Figure 5: *Setup at Temple University to conduct electrical tests of GEM foils performed by undergraduate students.*

GEM foil characterization - Optical scan / CCD camera setup The development of large single-mask GEM foil production requires the setup of dedicated optical measurement tools. The CCD camera setup, as shown in Figure 7 (a), is a microscope coupled to a 2D motorized support to scan GEM foils with high precision. The apparatus is controlled by a MATLAB graphical interface shown in Figure 7 (b). The first measurement of a 10×10 cm^2 foil produced at CERN has been successfully completed at Temple University by undergraduate students.

Figure 8 (a) shows the result of a scan with three extracted quantities:

- The distance between holes ('pitch'),
- the outer diameter and
- the eccentricity of the holes.

Starting from the left, the first graph shows the hole diameter distribution with a mean of 42 μm. The second graph shows the pitch with a mean of 117 μm. These values differ from the expected diameter of typically 50 μm and a pitch of about 140 μm. This is due to the fact that the absolute calibrations in both transverse coordinates has not been completed yet. The third graph of Figure 8 (a) shows the measured eccentricity, the 'roundness' of the holes. Figure 8 (b) shows the eccentricity over the complete $10 \times 10\,\mathrm{cm}^2$ foil.

The same foil has been used to produce both Figures 8 (c) and (d) with the difference that the foil has been artificially stretched along the bottom-left to the upper-right corner. This produced a visible gradient of the eccentricity values. This measurement provides therefore a means to ensure a proper hole geometry after stretching GEM foils.

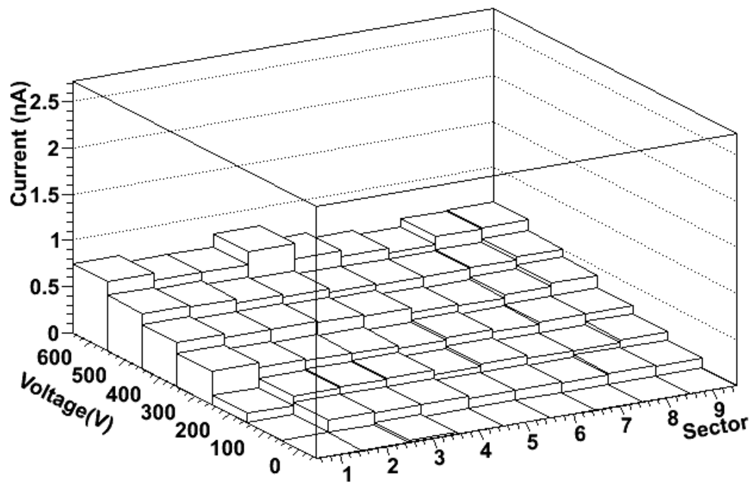


Figure 6: *Measured leakage current as a function of voltage and sector (1-9) for a GEM foil (Tech-Etch) of the STAR Forward GEM Tracker.*

Assembly of small triple-GEM prototype chambers In order to test GEM foils inside a detector, two triple-GEM prototype chambers of $10 \times 10\,\text{cm}^2$ have been assembled by undergraduate students at Temple University as shown in Figure 9. A closer view of one of these chambers is shown at the bottom of Figure 9, these detectors have been used in a cosmic ray setup shown in Figure 10.

Cosmic-ray test setup To test the tracking capabilities of the detectors, a cosmic-ray test bench has been setup at Temple University, shown in Figure 10. Two plastic scintillators plates cover an area of 60×40 cm^2. The coincidence between both scintillators provides a trigger signal for the cosmic-ray setup. On the top of this system, a 10×10 cm^2 prototype triple-GEM detector is mounted and placed on top of a 1 cm thick iron plate used to enhance the high-p_T range of the cosmic-ray spectrum. Coincidences between the GEM detectors and the trigger signal have been observed. This system is the basis of a future tracking telescope that will be used to characterize larger triple-GEM detectors with cosmic rays.

^{55}**Fe-source scan setup** Gain calibration is an essential tool to characterize a triple-GEM detector. By using the double-peak structure of a X-ray energy spectrum of an ^{55}Fe-source, one can measure precisely the absolute gain of a triple-GEM detector. The automation of such a measurement has been enabled by the purchase of a Multi-Channel analyser coupled to a precision pre-amplifier (ORTEC 142A) and a pulser for calibration. With the large active area foreseen for the next generation of triple-GEM detectors, it will be necessary to have multiple gain measurements to insure gain uniformity. With the help of a XY scanning table, shown in Figure 11, we are developing an automated measurement to produce a 2D gain calibration map. This map will have the advantage of taking into account all type of gain fluctuations due to the GEM amplification stage, the thickness of the induction gap and the large capacitance variation inherent to large GEM detectors. This gain map could later be used for data correction and tracking improvement in an experiment.

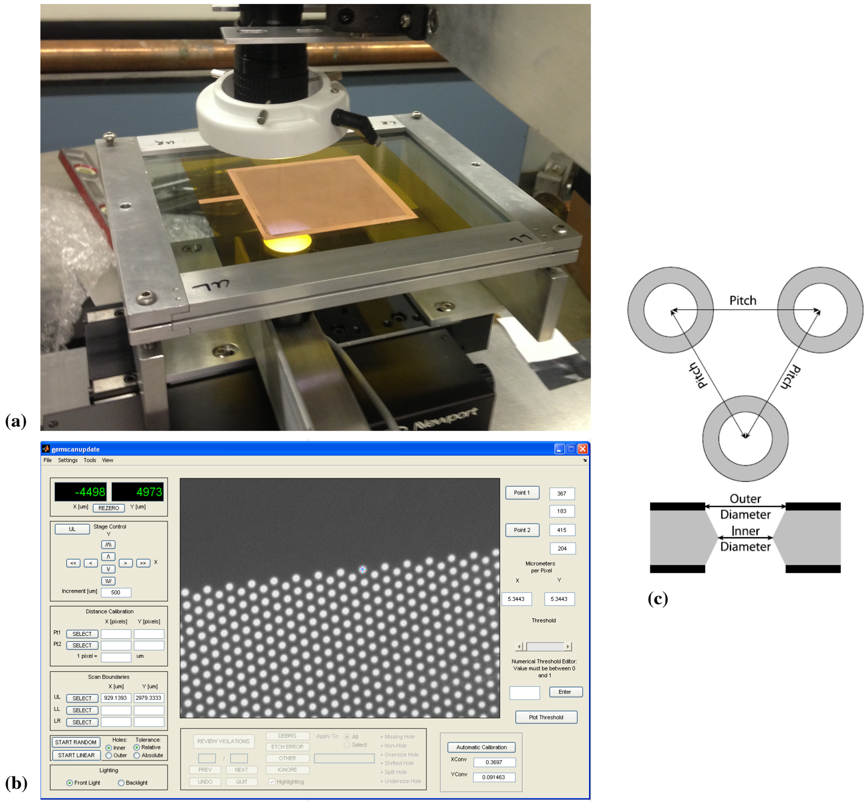


Figure 7: *(a) Gem foil scanner, (b) User interface and (c) Hole geometry of a GEM foil.*

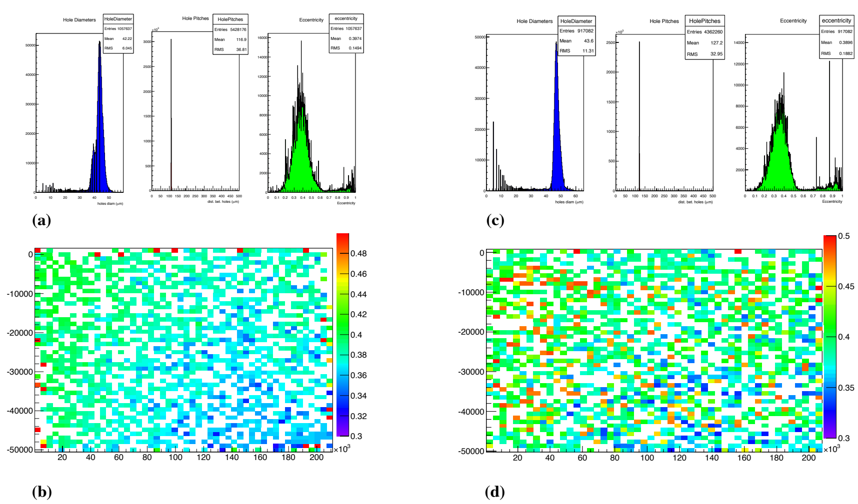


Figure 8: *Distributions of three measured quantities: Holes diameter, hole pitch, and eccentricity (a) and 2D map of the eccentricity value for a new stretched foil (b). Distributions for a stretched foil along the bottom left to the upper right corner are shown in (c) and (d).*

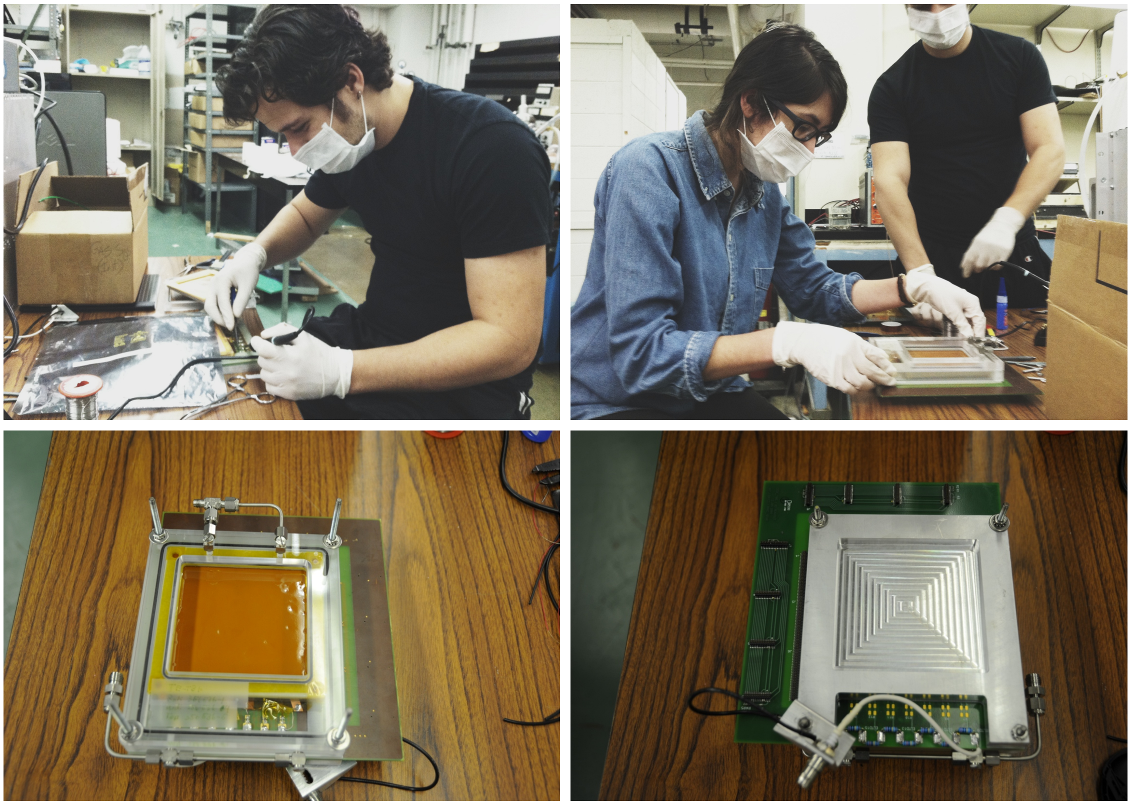


Figure 9: *Assembly of triple-GEM prototype chambers of* $10 \times 10\, cm^2$ *by undergraduate students at Temple University.*

Setup of APV-chip DAQ system A complete DAQ system has been almost set up at Temple University which is based on a copy of the STAR Forward GEM Tracker (FGT) DAQ system. A photograph of the STAR FGT crate is shown in Figure 12 (left). An identical modified Wiener VME crate is shown in Figure 12 (right) located in the Temple University lab. Besides the actual DAQ system, the crate provides also three slots for ISEG HV supplies of eight channels each. The DAQ system and HV system will be completed by summer 2013. In addition to the actual hardware, the full run control software along with slow control software and GUI for HV and gas control and monitoring will also be available.

Mechanical design of large triple-GEM detector segment and support structure The design of the next generation of triple-GEM detectors for an EIC detector requires minimal dead material and good uniform acceptance. The mechanical design therefore focuses on light weight materials and overlapping detector segments. A triple-GEM detector is inherently light. It consists of a stack of Kapton foils for the electrodes and GEM amplification, and Mylar foils for gas-tight enclosure, as shown in the exploded view in Figure 13 (d). Larger dead material is generally introduced by electronics and services. The idea here is to place all electronics and service components on the outer radial region of the detector (Figure 13 (a) and (b)) providing full mechanical support. This leaves the remaining part of the detector to be extremely light and allows to keep structural support at a minimum inside the active area. The layout of a GEM foil with 11 segments is shown

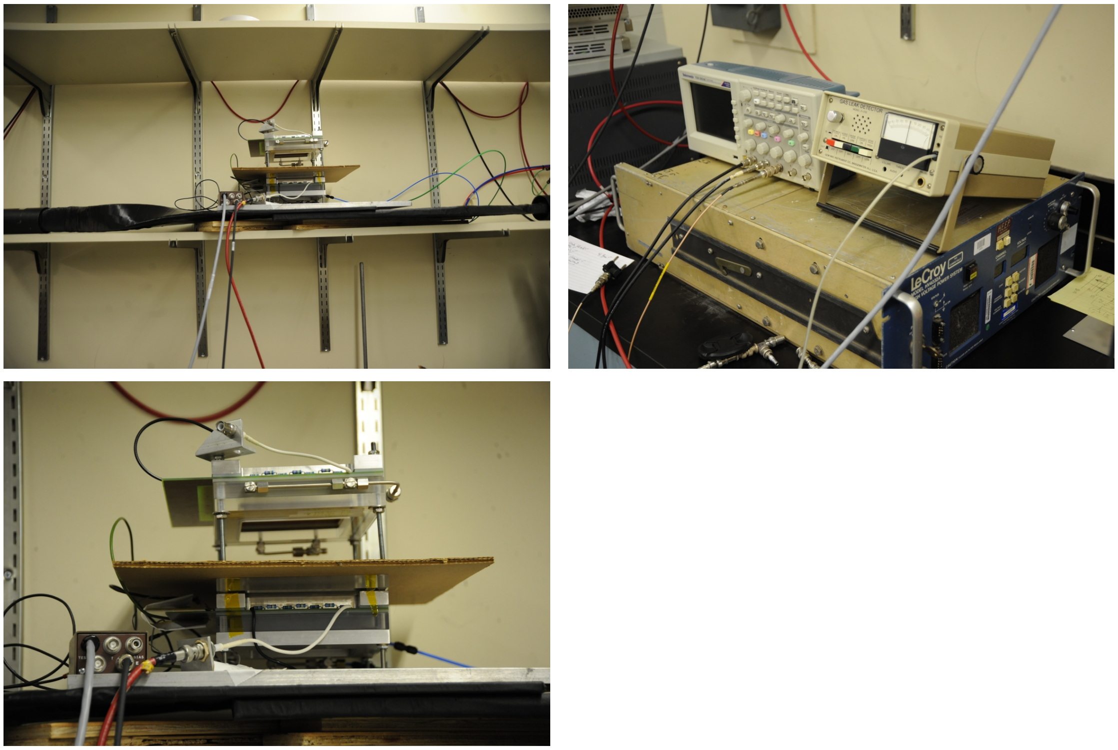


Figure 10: *Cosmic-ray setup at Temple University using* 10×10 *cm*^{2} *prototype triple-GEM detectors.*

in Figure 14.

Each long segment will be supported on a wheel-like carbon-fiber structure as shown in Figure 15 (a) and (b). The chambers are stacked face-to-face to provide easy access avoiding dead areas between detectors as shown in Figure 16 (a)-(e).

Commercialization of single-mask GEM foil production The commercial fabrication of $10 \times 10\,\mathrm{cm}^2$ GEM foils along with larger GEM foils has been established by Tech-Etch Inc. in collaboration with BNL, MIT, Temple University and Yale University. The actual fabrication employs glass masks for the photolithographic process for a given user defined layout of GEM foils using a standard Gerber-file. The chemical etching is based on a double-sided etching process. It has been pointed out by the photolithographic workshop at CERN that larger sizes are limited by this process requiring very precise alignment of both masks on either GEM foil side [3]. It has therefore been suggested to use a single-mask production process. This process has been established at CERN [4].

The Nuclear and Particle Physics community requires large quantities of large-size GEM foils such as for the upgraded CMS muon system and the ALICE TPC upgrade and eventually for an EIC detector. The CERN photolithographic workshop has therefore started a collaborative process with Tech-Etch Inc. to transfer the CERN technology to Tech-Etch Inc. with the goal in mind to provide commercially produced large GEM foils. The management at Tech-Etch Inc. signed all technology

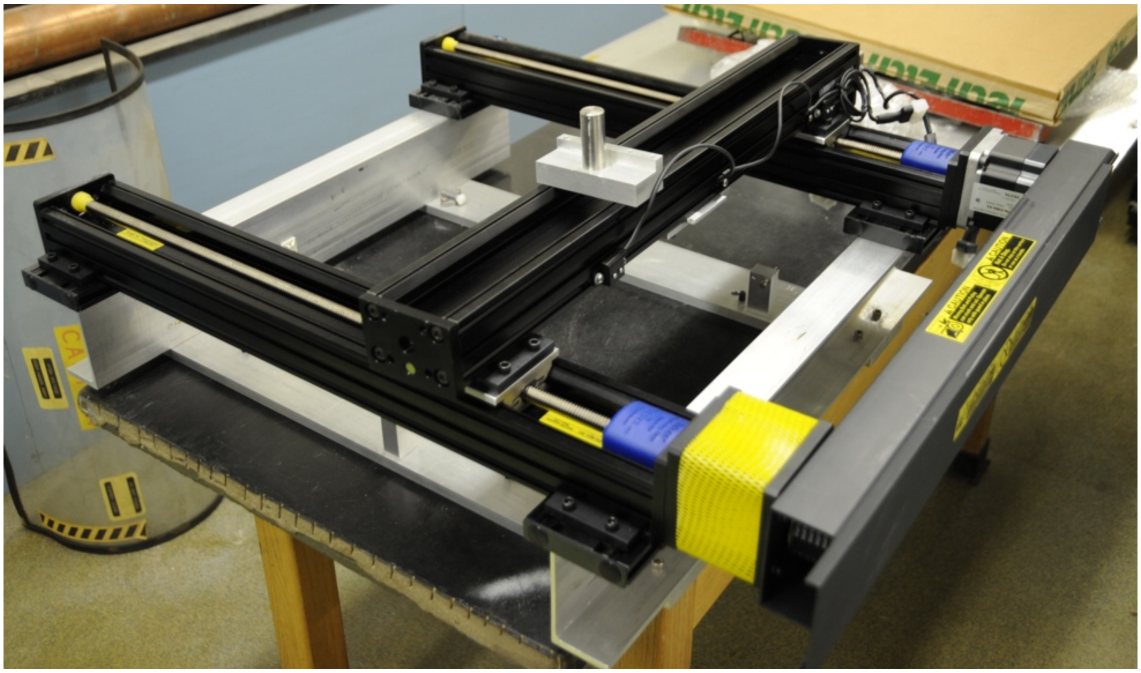


Figure 11: *Scanning table setup for a ^{55}Fe source scan of large GEM foils.*

transfer agreements. The Temple University group agreed with the Tech-Etch management to start the process with the single-mask production of $10 \times 10\,\mathrm{cm}^2$ GEM foils followed by FGT-type GEM foils based on existing Gerber files. It was greed that the Temple University group will test those foils and provide feedback to optimize the single-mask production at the Tech-Etch Inc. production plant.

The production of larger foils is generally limited to a width of about 50 cm due to the size limitation of Kapton base material distributed on standard-size rolls. Going to larger sizes such as those required for future EIC applications requires an upgrade of the production line at Tech-Etch Inc. including the purchase of new imaging and larger chemical etching bath setups. This process would clearly benefit from a new SBIR[3] proposal which will be certainly submitted by Tech-Etch Inc. in collaboration with BNL, MIT, Temple University and Yale University provided that the strict company size limitation of 500 employees can be solved. This issue has been brought to the attention recently to the DOE NP SBIR program manager. A major commitment that Tech-Etch Inc. has already been made in recent discussions with the Temple University group is the fact that Tech-Etch Inc. will develop the large-size single-mask production of GEM foils even if SBIR funds would not be available.

[3]Small Business Innovative Research, US-DOE funded program to foster collaboration of small companies and research institutions

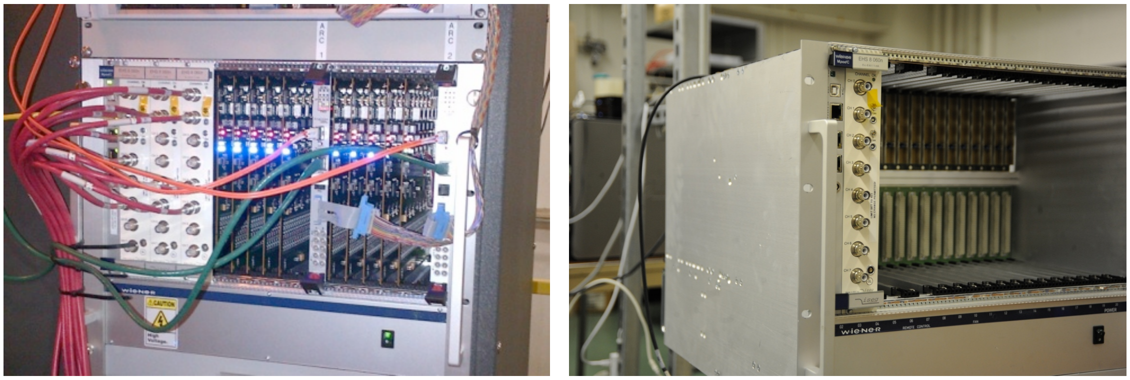


Figure 12: *Photograph of the STAR FGT crate (left) and identical modified Wiener VME crate located in the Temple University lab (right).*

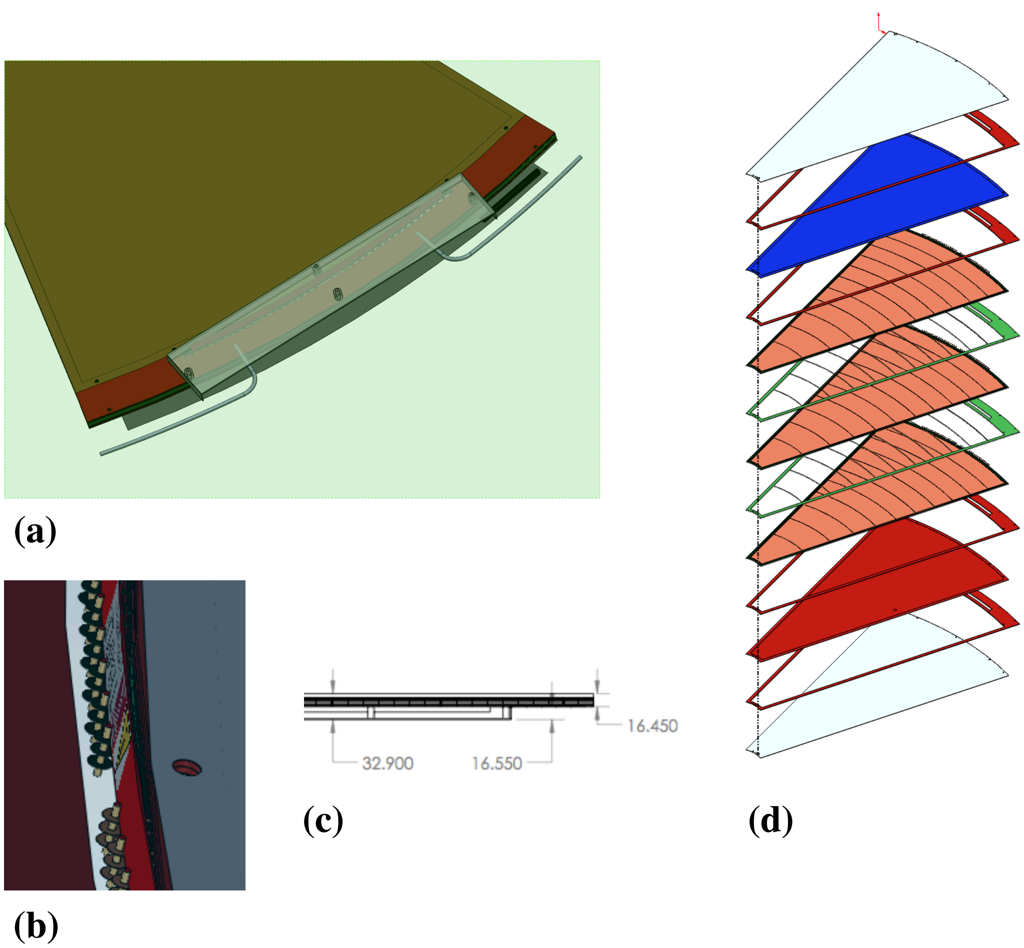


Figure 13: *Detailed view of segment design.*

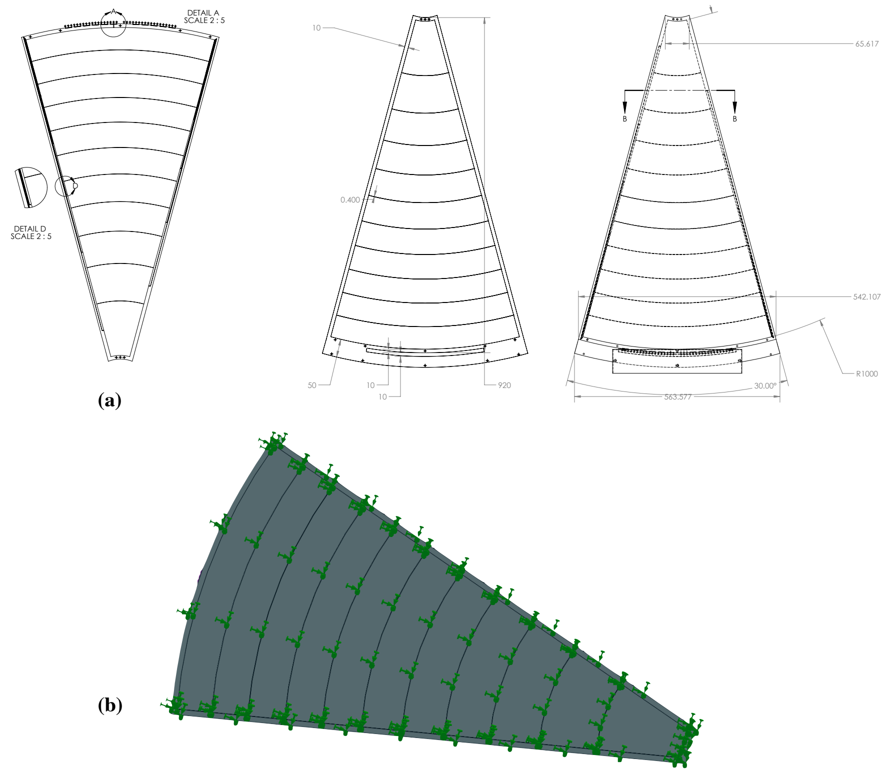


Figure 14: *Layout of large segment GEM foil with 11 sectors.*

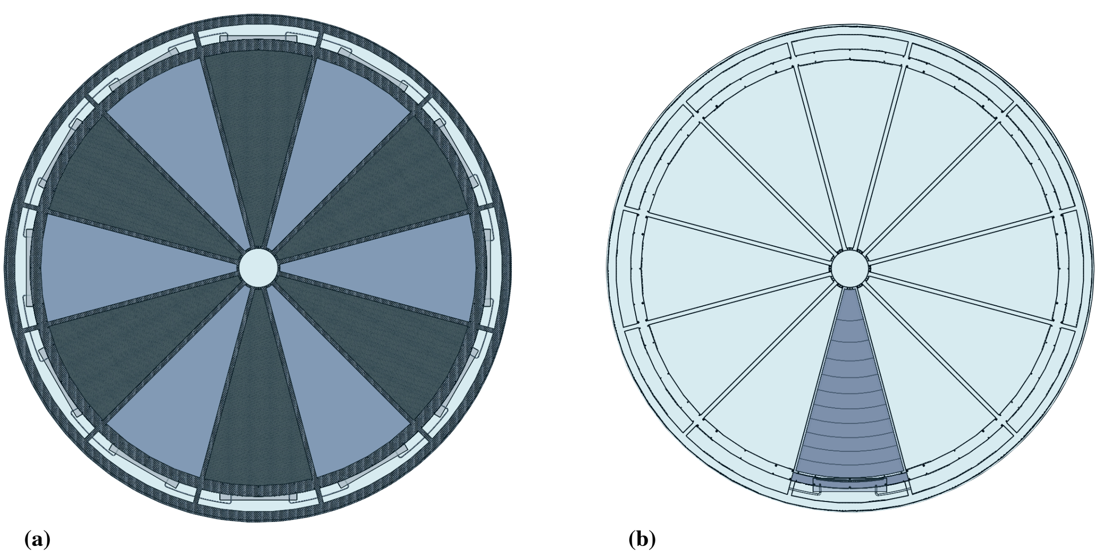
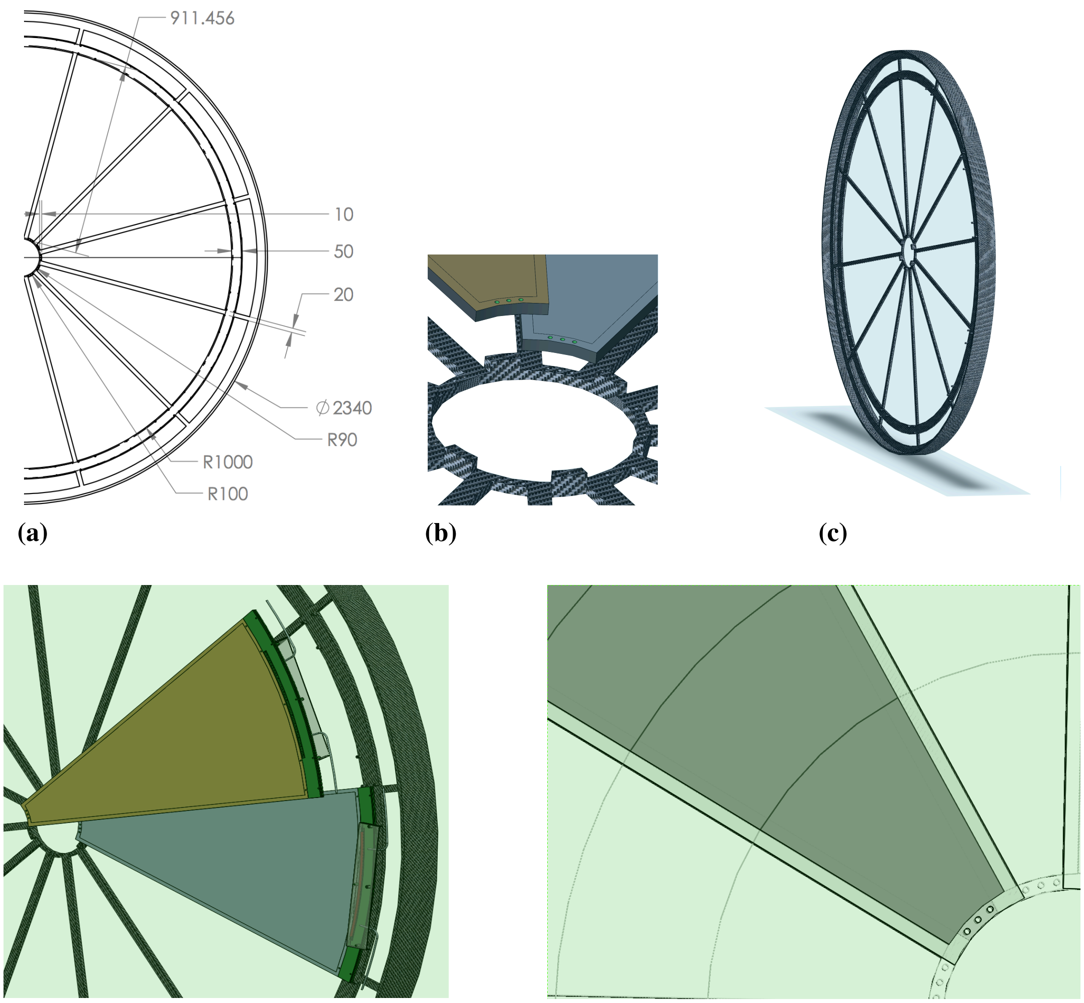


Figure 15: *Disk layout of 12 large triple-GEM detector segments.*



(a) **(b)** **(c)**

(d) **(e)**

Figure 16: *Details of disk dimensions and support of individual triple-GEM detector segments.*

2.2 Barrel MicroMegas tracking detector development

Almost all of the FY2013 R&D efforts for our proposal was put towards the forward GEM detectors, as initially planned. However, part of the development steps proposed for the Micromegas barrel could still be achieved in this first phase of our proposal, thanks to the large synergy with the Jefferson Lab CLAS12 project.

Large resistive bulk detectors Two flat prototypes (forward disks) have been built, one by CERN and one by the CIREA company for the CLAS12 project. These disks with 50 cm in diameter (CLAS12 dimensions) include a total of 1000, 500 μm thick resistive strips. The first results are very promising. The bulk process which comes after the production of the resistive PCBs are ideal for both the CERN and the CIREA prototypes. Both of them were fully functional, showed very high gain with no significant sparks, as well as high efficiency. The CERN prototype is shown on the left of Figure 18. The efficiency, measured using the MIP spectrum in a cosmic-ray test, is shown on the right.

Large size flex cables for readout As part of the CLAS12 projects, we have tested several prototypes of cable assemblies composed of micro-coaxial cables provided by two companies (SAMTEC, HITACHI). Very recently, 2 m long pre-series prototypes built as flat assemblies of 64-channel micro-coaxial cables from HITACHI have been tested. Our results are again very promising. These cables with 64 channels are light-weight (8 g/m) with very low capacitance of 40 pF/m. Samples of flex cables from HITACHI behave as expected. An example is shown in Figure 19.

	Dream Chip	APV25-S1 Chip
Number of channels	64	128
Memory size	512	160
Latency	16μs	8μs
Noise (e-RMS)	2100 (On 180pF)	1200 (On 20pF)
Sampling frequency	1-40MHz	10-50MHz
Dynamic range	50-600fC	150fC
Input capacitance	150pF	18pF
Shaping time	70ns	50ns

Figure 17: *Comparison of main chip parameters for DREAM and APV25-S1 chips.*

Tests of the v0 DREAM ASIC Figure 17 provides a comparison between the Dream Chip and the APV25-S1 chip. The APV25-S1 chip is no longer available and will not be produced any longer. The Dream chip is a dedicated development for micro-pattern detectors in contrast to the APV25-S1 chip which was primarily developed for silicon-strip detectors at CMS. The first batch of 380 ASICs has been received in November 2011. A number of tests have been conducted, which are all promising. The functional design of the chip has been validated, in particular the memory management allowing for the simultaneous sampling and reading of the signal, as well as the data storage in order to accomodate a 16 μs latency at 20 MHz. For the large prototypes described above, using 1.5 m long flex-cables, the S/N ratio has been increased by 15-20% compared to the previous generation electronics chip, *i.e.* the AFTER ASIC used for the T2K experiment. Even though the tests have proven that the v0 version of the chip was fully functional, a number of improvements can be made in order to improve the dynamic range of the DREAM chip by increasing the intermediate shaping time, correct a few minor bugs related to the coding of the synchronization information, improve the noise immunity through the improvement of the internal current sources and finally add new functions linked to self-triggering capabilities of the chip by adding the possibility of triggering on the multiplicity as well as on each channel individually. The new DREAM design v1 has been submitted for production in March 2013. The batch of 360 chips is now being packaged and is expected in June 2013. Finally, a second batch of v1 chips will be submitted for production in the fall of 2013. More details on the electronics development will be provided in the proposal Chapter 3.2.

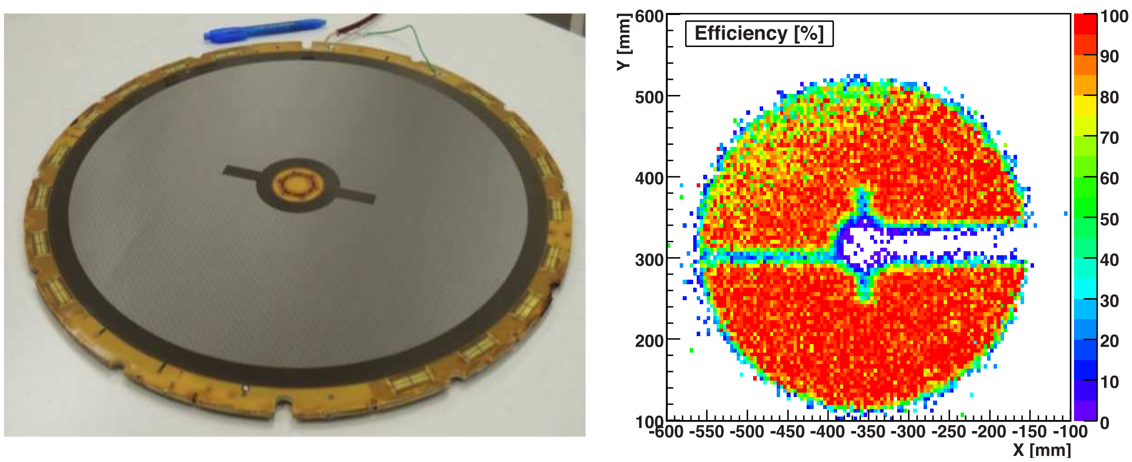


Figure 18: *First CERN prototype of a forward CLAS12 detector in the resistive bulk technology (left). Efficiency to MIPs (right). The lower efficiency area is due to a gas leak during the tests.*

In summary, all developments are very promising for our EIC R&D proposal and completes the first phase of our program.

Figure 19: *Different samples of flex cables from HITACHI. All cable assemblies are composed of micro-coaxial cables and provide an ideal solution for light-weight low-capacitance multi-channel cables.*

3 Proposal - FY14

3.1 Forward GEM tracking detector development

3.1.1 Commercial production and test of single-mask GEM-foils

The need for large GEM foil production using single-mask manufacturing techniques has been already introduced in chapter 2.1. Figure 20 shows the layout of the segmented and unsegmented side of a GEM foil segment. Each segment is further divided into 11 individual sectors. The HV connection for each sector is routed on the outer edges separately for even and odd sectors ending up in pin connections on the outer radial area. The planned steps are as follows:

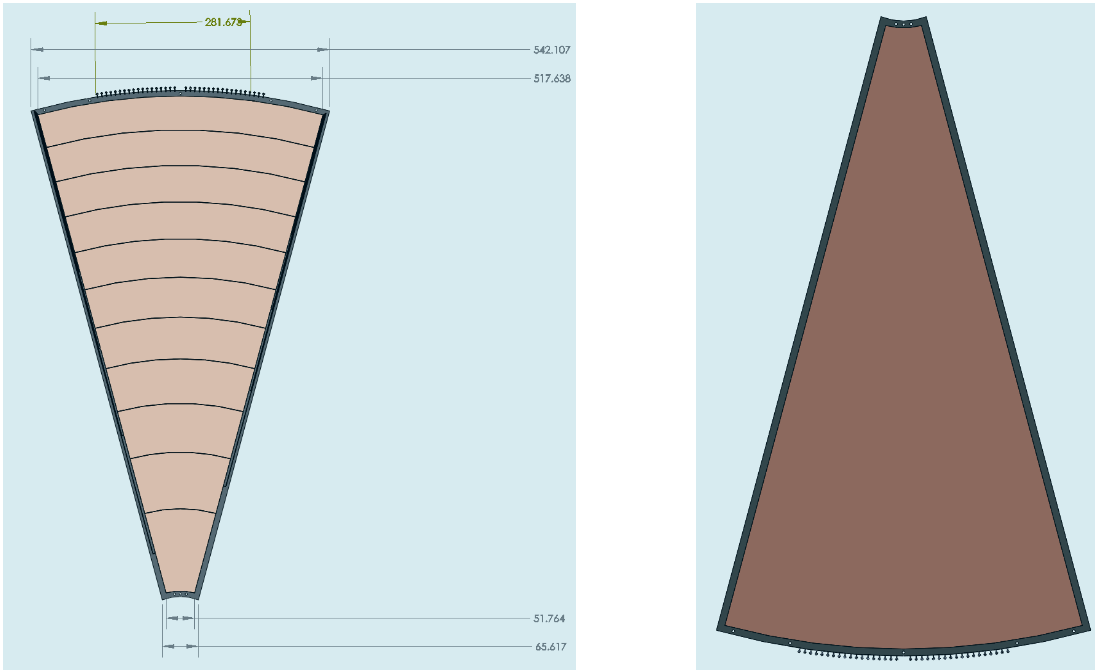
- Finalize mechanical design and verify design by MIT Bates engineering staff
- Prepare Gerber files for GEM foil segment
- Discuss design with CERN photolithographic workshop and order three foils
- Test CERN foils for electrical performance and optical uniformity

At the same time, it is planned to start the process of testing 10×10 cm^2 foils and FGT type foils produced by Tech-Etch Inc. using single-mask production techniques and compare those results to double-mask produced GEM foils. The production of larger foils than FGT type foils requires an upgrade of the imaging and chemical etching bath setup. It is not clear yet, when this will be completed during the fiscal year 2014.

3.1.2 Commercial production of large 2D readout foils

The layout of the large triple-GEM detector segment follows in spirit the STAR Forward GEM Tracker design [5]. The FGT does not use a solid 2D readout plane, but a 2D readout foil which has been manufactured by Tech-Etch Inc. based on a separate SBIR grant. Figure 21 shows the main components of the Gerber file of this 2D readout foil providing radial and azimuthal coordinate measurements in one plane using a large number of VIAS connections routed to multi-pin connector pads. Initial discussions with Tech-Etch Inc. indicated that extending the FGT 2D readout foil in size is not an issue. However, an upgrade of the production facility might be as well needed. The layout of the 2D readout plane will be driven by the hit resolution requirement for an EIC detector. It is anticipated that a hit resolution of about $100 - 200\,\mu$m is needed.

It is planned to discuss the Gerber file design also with CERN and order one 2D readout plane, simply to compare the results of a foil layout to a solid board layout.



(a) **(b)**

Figure 20: *GEM foil layout of large triple-GEM segment showing the segmented side (a) and un-segmented side (b). The location of HV pins can be seen at the outer radial region in both drawings.*

3.1.3 Design, production and test of spacer grid configurations

Introduction Two problems in realizing large area GEM detectors is maintaining a uniform gap between foils and holding the foils flat. The gap between foils, for a given high voltage configuration, determines the electric field between foils. This in turn determines the amount of charge entering and exiting the holes in the GEM foils and hence the gas transfer. Thus, the gap determines the gain of the GEM detector. For a typical GEM foil gap of 2 mm a variation around ± 0.3 mm is acceptable. Holding the foils flat is also important to avoid areas with wrinkles or creases that could lead to electrical breakdown or discharges that could damage the GEM foils or readout electronics.

In the past the gap and flatness of GEM foils have been maintained by stretching the foils across frames and using spacer grids between the foils. Stretching the foils across frames has a number of disadvantages. The frames must be designed to support the tension used in stretching the foils. For large area GEM detectors this could mean large tensions requiring substantial frames. The frames may then become a significant, dead area of the total detector. Also, if the detector geometry is not regular, stretching may introduce wrinkles either during stretching or afterwards when the foils are transferred from the stretching jig to the assembly jig. Spacer grids help maintain the gap between foils by supporting the foils at intermediate points. They also overcome problems with the foil sagging under gravity or from electrostatic forces. Typically these grids are on the order 10×10 cm^2 with wall thickness around 1 mm. In operation, the wall thickness produces a dead area two to three times the wall thickness corresponding to approximately 5 % of the active area.

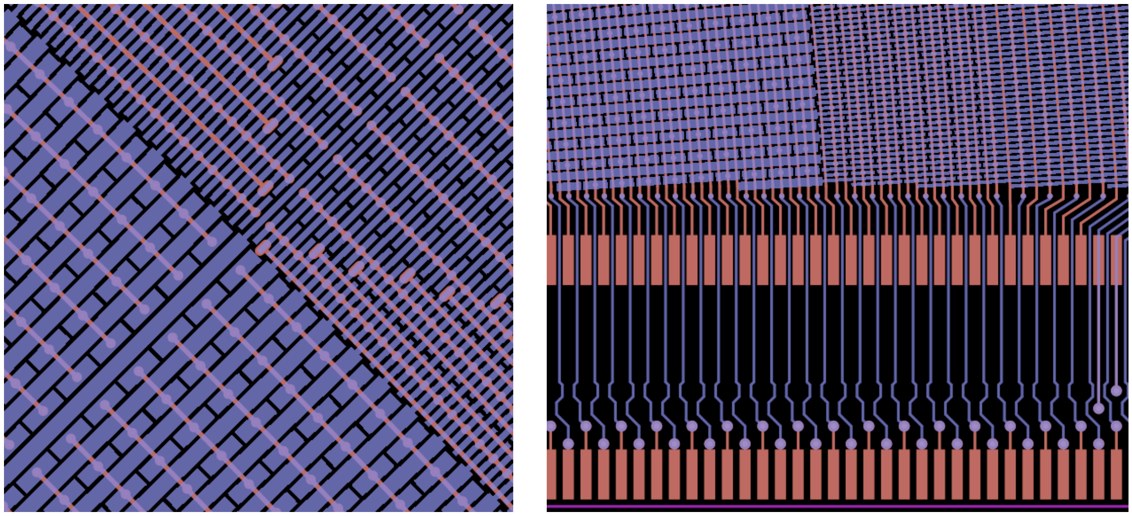


Figure 21: *Details of 2D readout foil layout based on the STAR Forward GEM Tracker showing the radial and azimuthal readout structure along with the pad layout connected multi-pin connectors.*

To avoid these problems we would like to investigate the possibility of using arrays of thin-walled polyamide (e.g. Kapton) rings between the GEM foils to support foils without stretching the foils. GEM foils, as produced by Tech-Etch, are basically flat. If you place a new foil on a table, it lies flat. So long as they are handled carefully the foils stay flat provided they are uniformly supported. We propose that an array of thin Kapton rings can be made to provide sufficiently uniform support that the foils remain flat and that the gap is held uniform without stretching the foils. Obviously smaller diameter rings provide more uniform support. The task will be to find an optimal diameter.

The Kapton ring wall thickness would be 0.050–0.100 mm so ten times less than the normal spacer grid wall thickness. However, to support the foils without stretching the rings would be smaller than the 10×10 cm^2 spacer grid area. Rings 25–50 mm in diameter would be tested. The net effect would be a smaller dead area in the active area and also a smaller non-instrumented area for the total detector area by eliminating a large area of the frames needed for stretching.

The following sections give more details for the proposed study.

Kapton Rings Kapton tubing is readily available in a variety of diameters and wall thicknesses. Various manufacturing companies can cut this tubing to the specified lengths with high tolerance and some can also laser drill holes in the sides as well. As an alternative other firms can produce Kapton strips with holes which can be glued to form the desired rings. We could also investigate the possibility of designing the tooling ourselves to cut tubing to the desired length with and without holes around the circumference.

The rings we are interested in using are 25–50 mm in diameter with 0.050–0.100 mm wall thickness. We would require two lengths or heights: 2 mm for the gap between the GEM foils and 3 mm for other gaps in the GEM detector stack. Some simple sketches are given in Figures 22 and 23 to provide an impression for the dimensions and aspect ratio of thickness versus diameter.

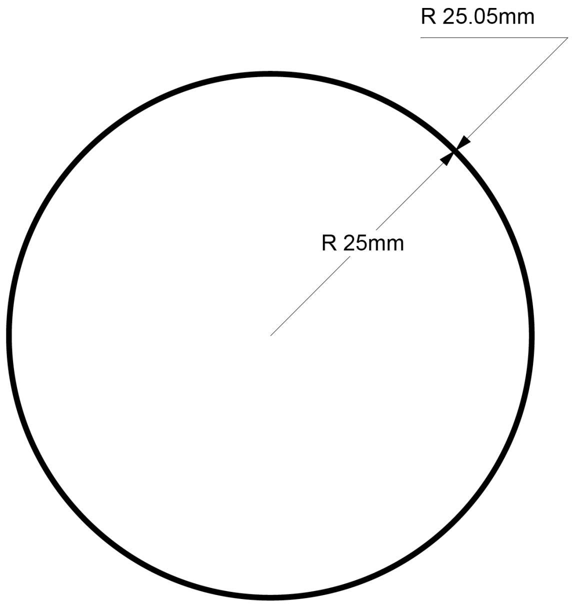


Figure 22: *Sketch of proposed Kapton ring showing the inner and outer dimensions for a 50 mm diameter ring.*

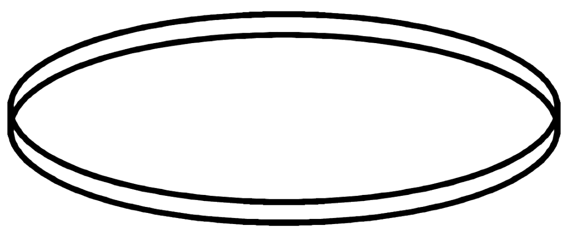


Figure 23: *Isometric sketch of proposed Kapton ring illustrating the aspect ratio for a 50 mm diameter ring with 2 mm height.*

Holes with 1 mm in diameter, around the circumference of the rings would be useful to allow gas to flow from side to side within a layer. Otherwise you would have to rely on gas flowing through the GEM foils from top to bottom. Gas flow is very important in the operation of the GEM detector as the foils are very hydroscopic and need good gas flow to remove water vapor before high voltage can be applied. Gas flowing from top to bottom through the GEM foils might be sufficient but might also be non-uniform and less efficient.

The Kapton rings can be arranged in various patterns as shown in Figures 24 and 25. Both configurations are stable when constrained by frames at the edges and provided the rings are prevented from overlapping each other during assembly and subsequent handling. Alternatively, the rings can be glued together at the contact points using a cyanoacrylate glue. Gluing should be done in advance on a flat surface. If the ring array does not fill the area between the frames the rings can be cut to fit or small rings inserted at the edges. Other glued arrays are also possible

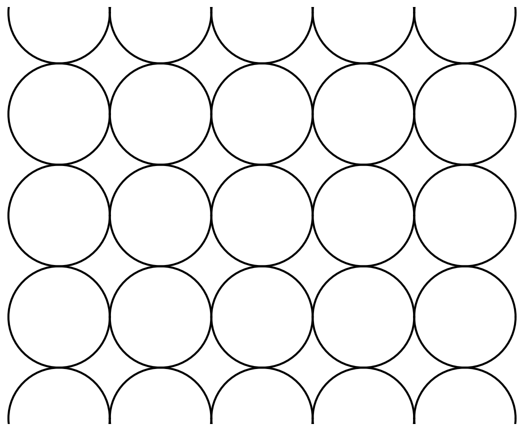


Figure 24: *Sketch of possible Kapton ring array.*

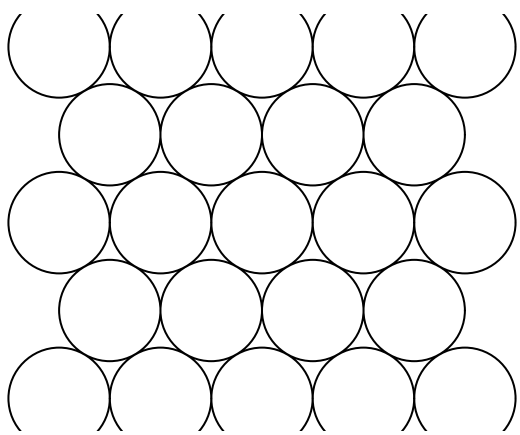


Figure 25: *Sketch of alternative Kapton ring array.*

such as shown in Figure 26.

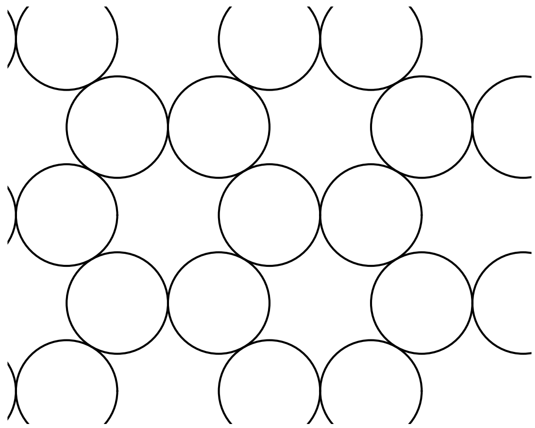


Figure 26: *Glued Kapton ring array requiring fewer rings for a given area.*

One possible supplier (Potomac Photonics) of Kapton rings with holes around the circumference has estimated the cost for producing a thousand rings at approximately \$2 each for an R&D proposal. This of course includes NRE costs and setup. The price for subsequent or larger orders would be less. For a large area GEM detector of $100 \times 50\,\mathrm{cm}^2$ around 200 rings would be required per layer. Even at \$2 per ring this is superior to the cost of manufacturing spacer grids.

If the foils are not stretched, the requirements for the GEM detector frames are much simpler. A gas volume must still be provided with inputs and outputs. Connections for high voltage are also necessary but these can be external to the gas volume. Some rough positioning of the GEM and other foils is desirable. Figure 27 illustrates one possible approach. The frame is only 10 mm wide

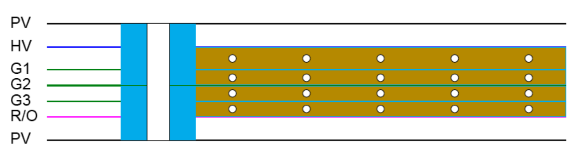


Figure 27: *Cross section of a possible GEM detector configuration at the edge near a frame.*

and its sole purpose is to provide a gas volume. This is achieved by gluing the stack together. An alignment pin is incorporated at a few places along the frame to roughly position the various foils. These pins do not constrain the foils or transfer any tension. Gas can be introduced and exhausted inside the pressure volume, PV, frames. The high voltage, HV, layer can be porous like a single sided GEM foil or the HV frames can route the gas flow to the other layers. Similarly, the readout layer, R/O, frame can route gas to the lower PV layer or it can also be made porous. The GEM layers, G1, G2, and G3, are of course porous. Gas flow can be realized from top to bottom through the foils but holes around the circumference of the ring, as shown, are desirable to help with uniformity.

In the scheme shown in Figure 27 the high voltage connections are assumed to be made external to the gas volume. Other schemes are of course possible.

Proposed R&D For the OLYMPUS experiment a large area GEM detector was developed but not completed because of time constraints. See Figures 28 and 29. These detectors consist of two

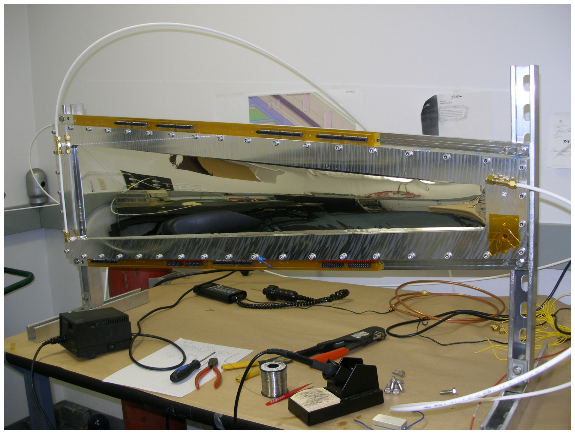


Figure 28: *GEM detector developed for the OLYMPUS experiment.*

trapezoidal GEM stacks inside a gas volume formed by an aluminum box with aluminized mylar windows. The GEM foils used were approximately 450 mm long and 250 mm wide at the widest end. This would serve as a test setup to study using Kapton rings to support GEM foils.

The OLYMPUS GEM detector is not necessarily the ideal choice. Modifications will be necessary for the gas flow. However, this approach should be significantly cheaper than developing a new detector configuration specifically to investigate this project.

To complete the study we would need to order some new GEM foils and the required Kapton spacer rings. The costing for this is outlined in Chapter 4.

3.1.4 Design, assembly and characterization of large triple-GEM detector segment

The design foreseen for an EIC forward tracking system consist of 12 chambers covering a disk of a 2 m in diameter. Each detector covers a 30° degree section from 10 cm (inner radius) to 100 cm (Outer radius) as shown in Figure 15. These dimensions give a maximum width of 54.2 cm for the GEM foil which stays within the produceable dimensions. The detectors will consist of a stack of GEM foils and kapton based electrodes glued together. An exploded view of the design is shown in Figure 13. The glued stack of 1 cm width FR4 frames in addition to the spacer grid is believed be enough to be self supportive and this design has been validated by MIT Bates engineers.

The first step in the validation process of this design will be the construction of an inactive chamber composed only of FR4 frames, spacers, and Kapton foils. The design of the relatively large frame has been discussed with companies specialized in water-cutting technics and the first samples will be ordered in the near future. It should be emphasized here that the spacer grid might change depending on the outcome of the Kapton ring studies which would clearly be preferred to simplify the whole assembly process.

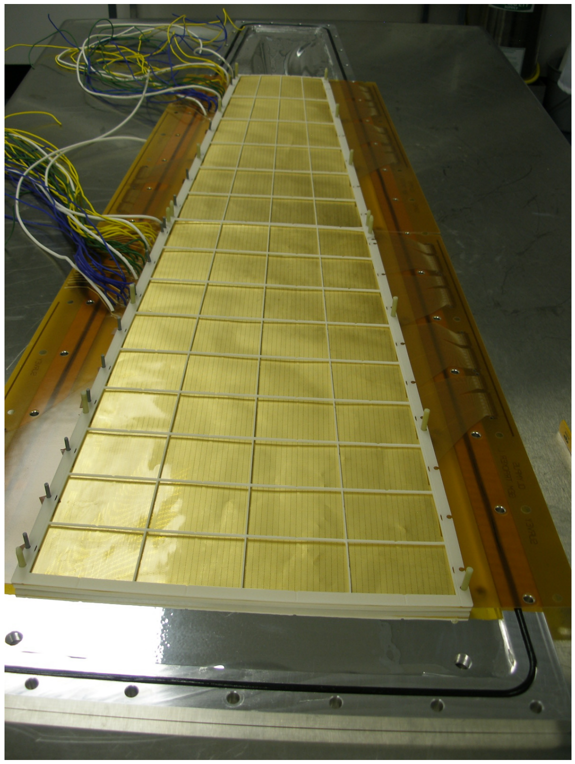


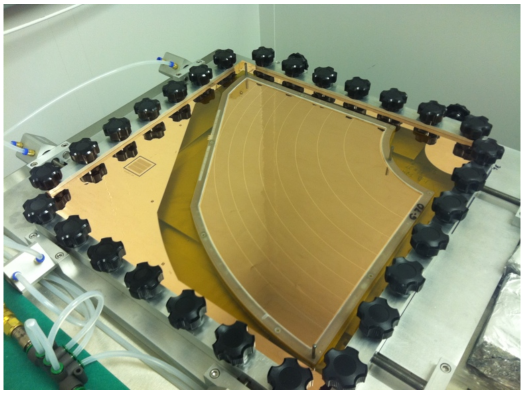
Figure 29: *View inside the gas volume of the OLYMPUS GEM detector showing the readout layer and one layer of spacer grids.*

The production of actual prototypes requires tooling similar to the ones used for the FGT detectors (Figure 30), scaled to the EIC dimensions. For glueing, a new stretching tool has to be designed, along with a longer gas tight box for leakage current measurements and a new support for the CCD camera setup.

These tools will allow that every GEM foil will be electrically tested and scanned. Gas leakage measurement will be performed on the assembled chamber in addition to a full electrical test with the connected HV distribution system. After passing these quality checks, the gain performance will be measured at several different points using the XY ^{55}Fe scanning table shown in Figure 11.

3.1.5 Design of light-weight support structure

The support of the twelve 30° segments assumes a 'wheel'-like support as shown in Figure 15. Preliminary discussions with an engineer from the MIT Bates engineer team point towards a solution based on carbon-fiber tubes taking advantage of the stiffness of this material. In addition to the lightness of the detectors, most of the detector weight will be located at the outer diameter where the chambers and its services will be supported by an external structure. The main purpose of the wheel is then to keep a rigid positioning of the self-supporting chambers. The Solidworks design will continue at Temple University with occasional reviews by the MIT Bates engineering team.



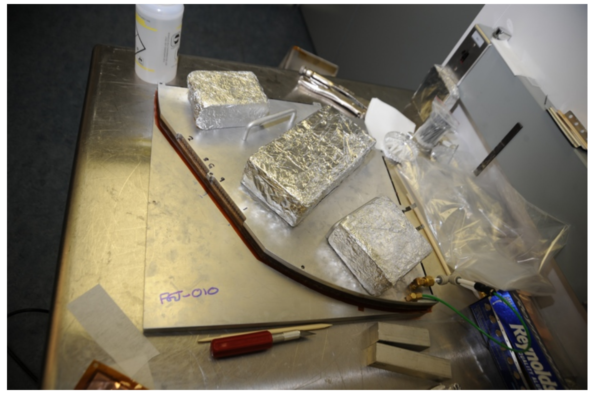


Figure 30: *Tooling setup for the assembly of larger triple-GEM detectors showing a stretching jig (left) and an assembly jig (right) for the STAR Forward GEM Tracker.*

3.1.6 Cluster size studies

The spatial resolution required at the EIC for the triple-GEM detectors is about $100 - 200\,\mu$m, which is a standard performance for a GEM tracking detector. The spatial resolution results from a complex combination of the distance between electrode (the pitch), the size of the electron signal, and the signal to noise ratio of the detector. As a result, it is difficult to predict the spatial resolution of the detector at the design level and high granularity (small pitch) is often used to ensure the best performances. However this means expensive readout boards, a large number of electronics channels, and therefore the need for power and cooling. The goal of this study is to reduce the granularity without compromising the performance.

Figure 31 (a) motivates the possibility of changing the width of the electron signal in a triple GEM detector by tuning the electron diffusion between foils. As shown in Figure 31 (d), the transverse diffusion in Ar/CO2 70/30 highly depends on the electric field.

The main idea is to adjust the electron cloud size, represented by the circles in Figure 31 (b), to the pitch of the electrodes. Figure 31 (c) shows the results of a simulation where one can see the influence of the width of the signal on the RMS of the residual distribution. This shows that after reaching a width of approximately half the pitch (here 0.04 cm), the spatial resolution reaches a plateau and the increase of the granularity will not improve the spatial resolution.

This simulation effort coupled with cluster size measurements using the cosmic-ray setup will allow us to reach the EIC requirements and at the same time keep the complexity and cost of the detector to the lowest possible.

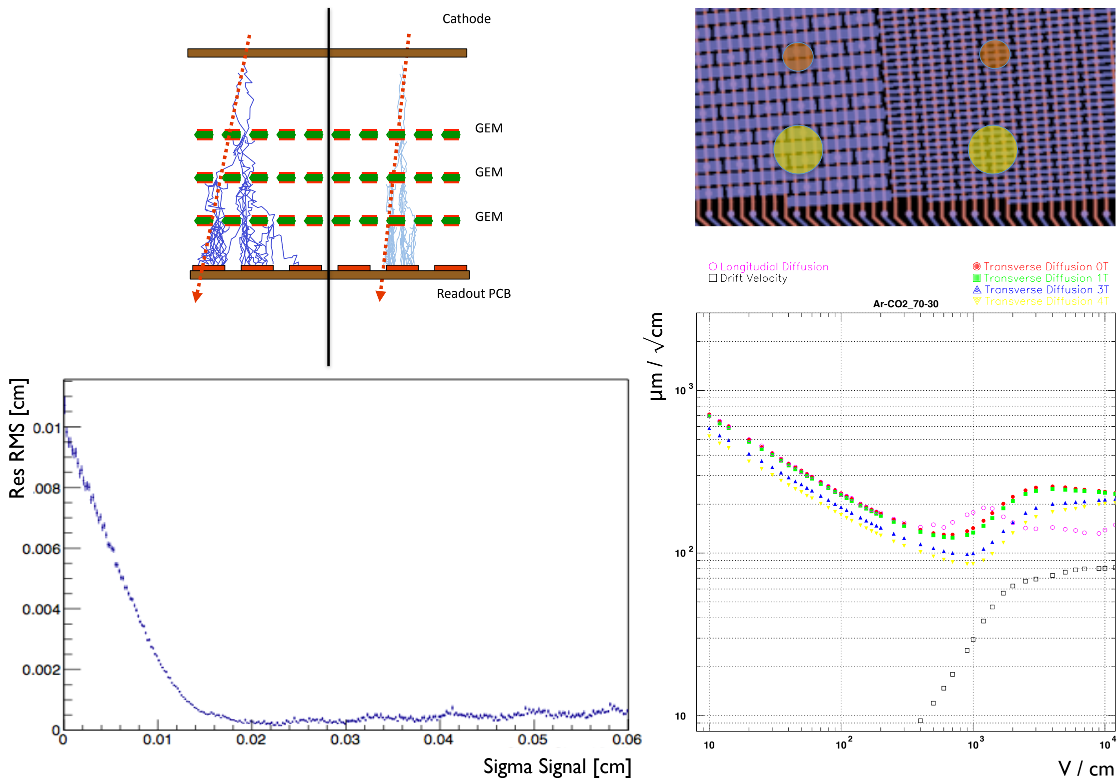


Figure 31: *Details on the cluster size studies: (Upper left) Effect of a lower electron diffusion in a triple-GEM detector. (Upper right) Projection of the resulting cluster size on the readout electrodes. (Bottom left) Simulated resolution of a detector with a pitch of* 400 μm *with respect to the cluster size (sigma of the gaussian distribution simulating the electron cloud). (Bottom right) Electronic transverse diffusion in Ar/CO2 70/30 with respect to the electric field [6].*

3.2 Barrel MicroMegas tracking detector development

3.2.1 From CLAS12 to EIC

A Micromegas (MICROMEsh GAseous Structure) is a gaseous detector based on a parallel plate electrode structure and a set of microstrips or micropixels for readout. The micro-mesh separates the amplification and the conversion gap. In the conversion gap, the particles interact with gas atoms to create primary electrons that drift towards the amplification gap creating an avalanche in the presence of a large electric field. A schematic of a Micromegas detector is shown on Figure 32. If this field is high enough compared to the field in the conversion gap, the micro-mesh is transparent for the electrons, but not for the ions coming from the avalanche. This special feature allows a very fast collection of the ions created in the amplification gap (around 100 ns, compared to several microseconds for a drift chamber). For this reason, Micromegas detectors have a very high-rate capability.

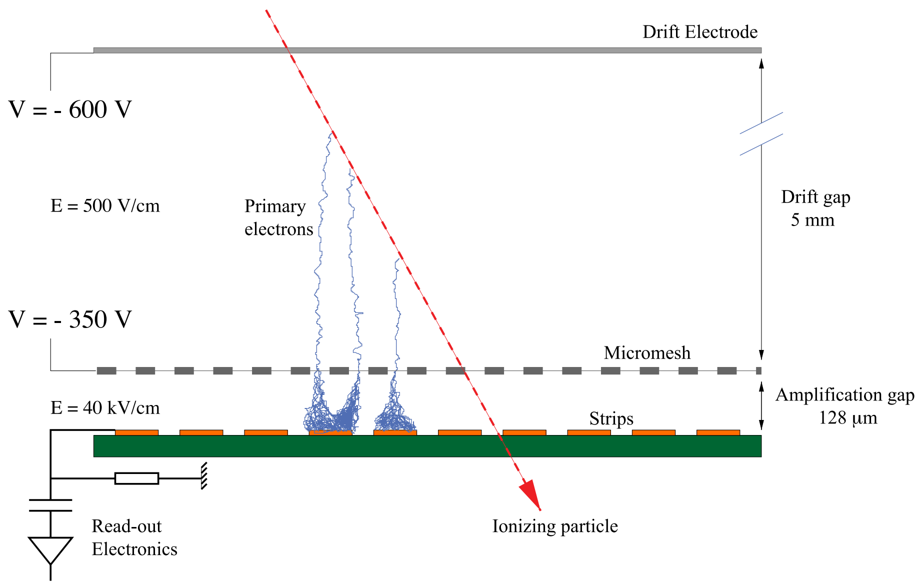


Figure 32: *Schematic of a Micromegas detector.*

The newly invented bulk technology for the Micromegas production adds to the advantages of such detectors profiting from the lamination of a Printed Circuit Board (PCB) with photo-resist films. After suitable insulation and chemical treatment, one obtains an array of spacers (pillars) that hold the mesh permanently in place, and ensure a constant distance to the PCB including strips or pixels over the whole sensitive area of the detector. Using this procedure, robust and large detectors can be easily built.

The end result is a lightweight detector, about 0.16% radiation length per layer, which has a very low cost, especially compared to Silicon alternatives. It can be made in large sizes, and due to the fact that the PCB may be relatively thin, and can even be curved in order to create cylindrical detectors. Such a detector is currently under production for the CLAS12 central detector at Jefferson Lab by the CEA Saclay group (Figure 33), and it is therefore natural to expend this R&D in order to study the case of an intermediate vertex tracker for the EIC.

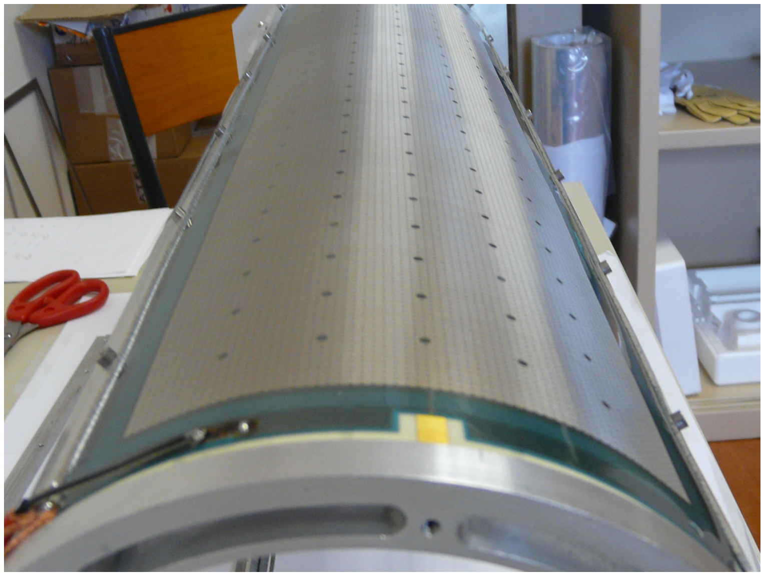


Figure 33: *Cylindrical Micromegas (without drift electrode) used as a prototype for CLAS12.*

The CLAS12 Micromegas Vertex Tracker is about 0.4 m long and 0.5 m at maximum radius. The EIC intermediate barrel tracker would probably be about twice as long at least and slightly larger in radius. This significant increase in size requires additional R&D, both in the production process but also in the readout electronics. The solution used in CLAS12 so far consists in 1 m-long flex and lightweight cables between the detectors and the front end electronics (analog + digital). These short cables are unlikely to be suitable for an EIC and other solutions will need to be examined. This R&D will be common with the forward and backward GEM detectors in this proposal, which will also need to be relatively lightweight and still have their electronics readout close enough to the detector.

3.2.2 Electronics for a Micromegas barrel tracker

The Micromegas detectors used for particle tracking can only be operated at low gain to limit the spark rates. This kind of technology permits the manufacturing of low-cost very large size detectors covering area up to 0.5 m^2. The anodes of these large detectors are usually segmented in long strips with capacitance of typically 100 pF, nearly one order magnitude larger than for silicon detectors. Moreover, this capacitance is increased by the cable length when moving the front-end electronics away from the detector.

The 64-channel DREAM ASIC (Figure 35 and 36), developed by CEA Saclay/ for the Micromegas tracker of the CLAS12 experiment, has been designed to fulfill the specific requirements of tracking using micro-pattern gaseous detectors with capacitance per channel in the range of 50-200 pF. Its specified noise is smaller than 1500 e^- for 100 pF detector capacitance (2500 e^- for 200 pF) for a

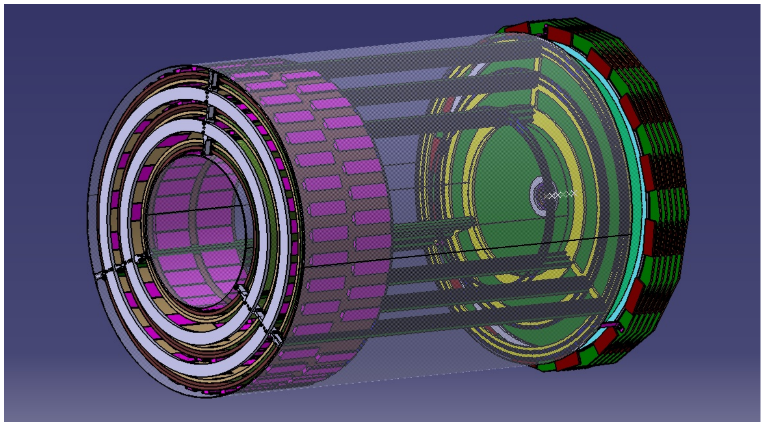


Figure 34: *CAD model for the CLAS12 Micromegas Vertex Tracker showing 3 double layers of cylindrical Micromegas detectors as well as forward chambers. The CLAS12 central detector also contains a μ-vertex detector in the center of this tracker (not shown). Both the total length and the diameter in this schematic are about 0.5 m. The readout electronics is connected to the detectors through 1 m-long flex cables (not shown).*

100 ns shaping time. Its very front-end part consists of a charge preamplifier able to sustain up to 20 MHz rate followed by a pole-zero stage and a filter with programmable shaping time from 80 ns to 1 μs. The gain of the chain is programmable among 4 values corresponding to measurement ranges of respectively 50 fC, 100 fC, 200 fC and 1 pC, such that it can operate in a wide range of detector gain or energy deposition. The output signal of the filter is sampled in an analog memory with a depth of 511 cells/channel at a rate up to 20 MHz This analog memory is used as both L1 latency and de-randomizing buffers operating in dead-time free mode as shown in Figure 37. The samples which are within a time window selected by the external L1 trigger signal (with programmable fixed latency up to 16 μs) are frozen and then read (in the order of their write time) without stopping the analog storage process. For one trigger, all the channels are read out. The number of cells of the corresponding readout window is programmable. The read samples are serialized in order to be digitized by an external 20 MSPS ADC. For a 16 μs L1 latency, a 20 MHz sampling rate and 4 samples read for each event, more than 32 triggered events can be stored in the analog memory (while the sampling is continuing) so that for a Poisson-distributed trigger rate of 40 kHz (twice the specification in CLAS12), the simulated dead-time is smaller than 10^{-7}. The readout of several samples for all the channels for each event permits to perform digital treatment in order to improve the signal over noise ratio. In particular, this allows to subtract the coherent noise between channels which is expected to be sizable on large detectors, in order to discriminate signal and noise using the pulse duration information or to detect pile-up events, and of course to calculate the signal's time. The CLAS12 front-end units (currently being designed), are carrying 6 DREAM chips, in compact (14 mm$\times$14 mm) plastic packages, the ADCs and a FPGA, managing the ASICs and performing a first level of digital treatment. The data from these boards will be collected by the MPD VME boards developed by INFN Genova, before being sent to the DAQ.

Even though DREAM is perfectly adapted to the use of Micromegas detectors with large capacitance, the use of such technology in the context of EIC requires additional developments:

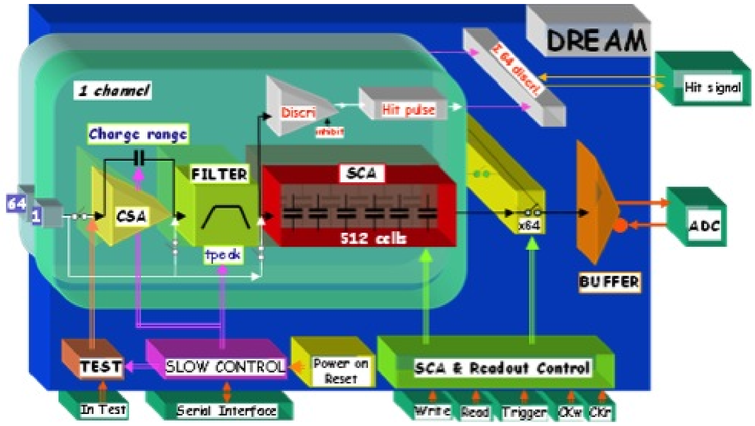


Figure 35: Block diagram of the DREAM chip.

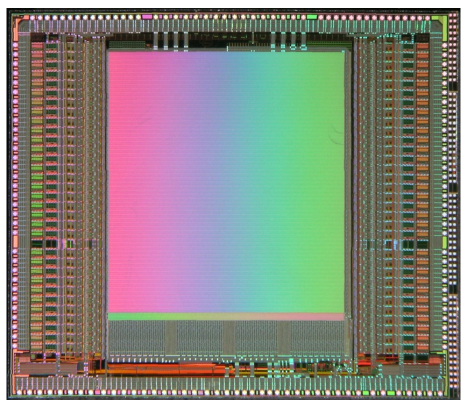


Figure 36: Photography of the DREAM chip.

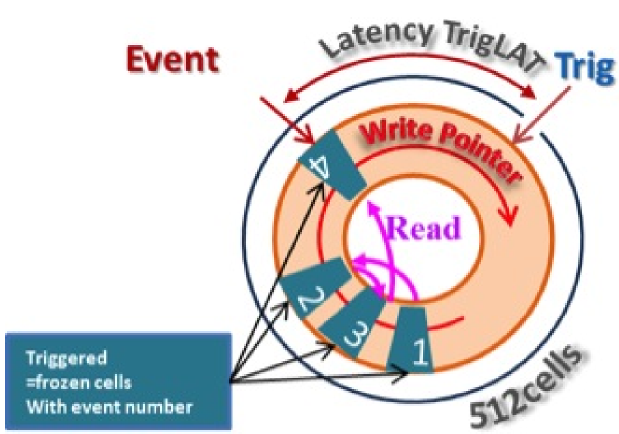


Figure 37: SCA used as a L1 circular buffer with frozen cells.

- In the CLAS12 experiment, the DREAM acquisition will use a L1 trigger built from the data of other detectors. This may not be possible in future experiments with an EIC and the tracker chips will need auto-triggering capabilities and the ability to provide fast signals usable to build triggers. This feature is already available in the DREAM chip, as each channel includes a discriminator. The discriminator outputs are red to form a HIT chip output. This functionality, legacy from the former AGET chip, is not used on the front-end units of CLAS12 and requires a special front-end board development. This study must be done using a real size detector with a special focus on the minimum achievable threshold and of this type of readout on the noise performances.
- In CLAS12, considering the very tight schedule and to minimize the risks, we have chosen to move the front-end electronics away from the detector with the penalty of the extra cost and noise due to long cables of the order 1 m. When using such detectors within the EIC detector, the space constraints will be higher and the electronics will be most likely be on the detector PCB itself. To minimize multiple scatterings, it will be necessary to reduce the material in the detector including electronics. For this purpose, we also propose to study a detector prototype read by bare DREAM chips directly bonded on PCB (standard bonding or stub bonding).

3.2.3 New R&D studies

We propose to study and build a large scale 60° section prototype (∼50 cm radius) and therefore do R&D on the following aspects:

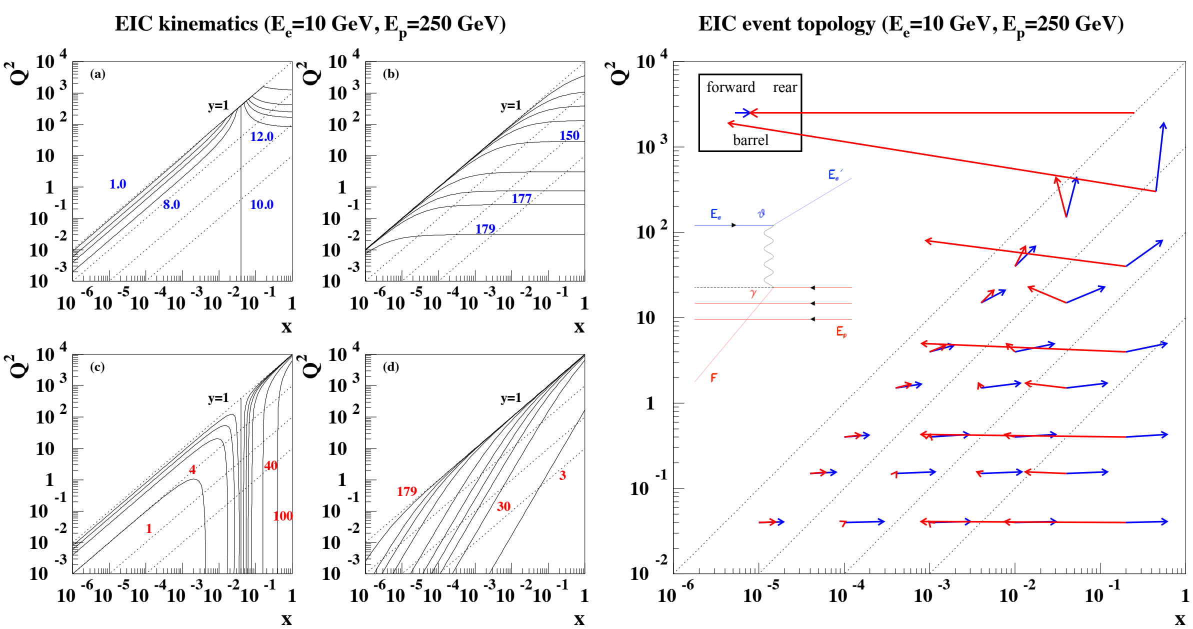
- Use of the resistive technology for curved detectors, which is a logical step beyond the 'metallic' solution planned for CLAS12.
- Studies of on-detector chip solution for the DREAM ASIC. In this framework, extra R&D has to be done in order to separate the DREAM chip itself from the digitization/signal treatment (done with a combination of ADC and FPGA chips). It is foreseen that a differential-pair of a few meters can be used to send the signal from the DREAM chip to the digitization card. This is crucially important to limit the power consumption of the electronics imbedded onto the detector.
- Studies of large-size cables for readout (beyond the 2 m cable length already studied for CLAS12), which in addition to the studies done on the separation of analog/digital parts, will allow for a long distance between the detector and most of the electronics.
- Design of mechanical structure similar to the CLAS12 barrel tracker. This includes self-supporting lightweight carbon structures to support the curved Micromegas detector which R&D has started in the context of CLAS12.

It should be stressed that this prototyping effort largely profits from the previous R&D made for the CLAS12 Micromegas Tracker project. However, the challenges of both the extension in size and of the readout electronics are critical to applying this technology to a future EIC.

3.3 GEANT4 tracking detector simulations

Two undergraduate students have started with the setup of a basic GEANT4 simulation to exercise various simulation tools. It is planned to use simulation tools provided by the BNL EIC group focusing on the outer barrel and forward tracking region which is the main focus of this proposal aiming for the following aspects:

- Implementation of barrel and forward tracking layers
- Study of hit reconstruction and transverse momentum resolution for different assumed readout structures for both the MicroMegas and triple-GEM tracking systems
- Study of kinematic variable resolution in addition to existing analytical acceptance and resolution studies as shown in Figure 38 for the case of 10 GeV electron on 250 GeV proton beams.



$$E_e/E_p = 0.04$$

Figure 38: *Analytical acceptance and resolution study showing the direction and size of the energy of the final electron and struck quark in the $Q^2 - x$ plane for different $Q^2 - x$ combinations.*

4 Budget and Schedule

4.1 Budget overview - FY13

Figure 39 (left) shows a break down of the main categories which the FY2013 grant of $\$150,000$ has been allocated to. The largest part concerns labor (‘Post Doc’) and travel (’Travel - Domestic (BNL/MIT)’). The main equipment items are shown on the right in Figure 39.

EIC R&D Items - Sabatie / Surrow (PI, Temple University)
Items FY2013 ($150,000)
Post Doc
Travel - Domestic (BNL / MIT)
Material
Equipment
Technician (TU CST)

EIC R&D Items - Sabatie / Surrow (PI, Temple University)
Equipment / Material Items FY2013
1 Oscilloscope
1 Spectroscopy amplifier
1 Pre-amplifier
1 Pulser
1 Multi-Channel Analyser
1 Soldering Iron
1 Clean Room / Portable
300 APV chips
1 DAQ computer
2 ROC DAQ card
2 SIU DAQ cards
Misc. items (Cables / Gas / Gas equipment etc.)

Figure 39: *Main budget categories for the FY2013 grant (left) and equipment items (right).*

4.2 Funding request - FY14

Figure 40 shows a complete breakdown of the FY2014 budget request:

- Total Direct Costs: $\$243,612$
- Total Project Costs: $\$295,108$

As shown in the pie chart on right side in Figure 40, the total labor category () is clearly the largest fraction.

The equipment and service items are shown in more detail in Figure 41. The largest service request refers to the Micromegas detector fabrication. This service request will allow the following:

- 3D design of a pair of curved resistive Micromegas bulk detector.

EIC R&D Overview - Sabatie / Surrow (PI, Temple University)	FY 2014
Personnel / Travel	Amount
Post Docs	$51,705
Undergraduate support	$20,880
Total Salaries	$72,585
Fringe benefits	$16,287
Total Personnel	$88,872
Travel - Domestic	$16,000
Travel - International	$21,000
Material / Equipment	
Material	$5,750
Equipment	$45,550
Other	
Services	$66,440
Total	
Total Direct Costs	$243,612
Modified Total Direct Costs (MTDC)	$198,062
F&A: 26%	$51,496
Total Project Costs	$295,108

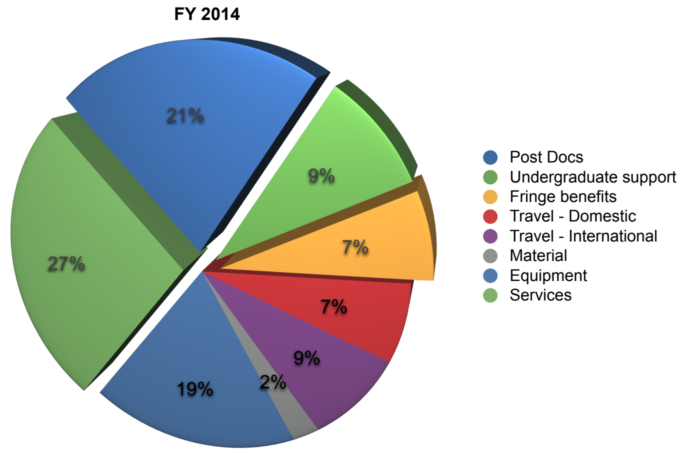


Figure 40: *Total budget breakdown (left) and chart in percent relative to the total direct costs (right).*

- 2D mechanical drawings of the curved resistive Micromegas bulk detector and the order of the mechanical components.
- 2D gerber design and drawing of the resistive PCB and the order of two such prototypes to CERN or CIREA, whichever is deemed best at the time of the order.
- Manufacturing and integration of the full detectors.
- Characterization of the prototypes with a ^{55}Fe source and cosmic-ray test.

The cost breakdown for the services provided by CEA Saclay are as follows for the total request of $\$41,000$:

- 2D and 3D studies : $\$9,000$
- PCB, drift electrode, mechanics : $\$17,000$
- Resistive bulk manufacture : $\$7,000$
- Integration and tests : $\$8,000$

4.3 Schedule summary

The graph in Figure 42 shows an overview of the schedule concerning the main activities of both the forward and barrel R&D efforts along with the work location for Dr. Maxence Vandenbroucke.

EIC R&D Equipment - Sabatie / Surrow (PI, Temple University)	FY 2014
Equipment Items	**Amount**
Particle counter	$500
Gas leak detector	$750
SolidWorks CPU	$2,750
Segment HV foils	$1,500
Segment GEM foils	$12,000
Segment 2D readout foils	$5,000
Radioactive source	$250
HV GEM foil distribution module	$500
Fume hood	$2,750
10 X 10 2D readout board	$1,250
10 X 10 APV board	$1,050
Kapton ring material	$4,000
Stretching jig	$4,500
Assembly jig	$3,250
HV N2 box	$3,750
Cables	$1,750
Total Equipment	$45,550

EIC R&D Services - Sabatie / Surrow (PI, Temple University)	FY 2014
Service Type	**Amount**
Technician (TU CST)	$15,840
Engineering support (MIT Bates)	$9,600
MicroMegas Production (Saclay)	$41,000
Total Service	$66,440

Figure 41: *Equipment (left) and Service (right) budget categories for FY2014..*

EIC R&D Forward and Barrel R&D Schedule	Time in Months for FY 2014											
Items	**10**	**11**	**12**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
(1) General:												
Dr. Maxence Vandenbroucke at Temple University	■							■	■	■	■	■
Dr. Maxence Vandenbroucke at CEA Saclay		■	■	■	■	■	■					
Test beam at FNAL	■											
(2) Forward triple-GEM R&D:												
Spacer grid studies (Frame) at TU	■	■	■	■	■							
Spacer grid studies (Kapton rings) at MIT Bates	■	■	■	■	■							
Complete 55Fe source scanner	■											
Finalize mechanical design and verify design at MIT Bates	■											
Prepare Gerber files for GEM foil segment	■											
Discuss design with CERN photolithographic workshop	■											
Order CERN foils		■										
Test CERN foils				■	■							
Order frame components				■								
Order HV foils		■										
Order and complete tooling setup		■										
Stretch of foils				■	■	■	■	■	■			
Design of 2D readout layer	■	■	■									
Order of 2D readout layer				■								
Assembly of segments						■	■	■	■			
Test of segments										■	■	■
Test of single-mask produced foils at Tech-Etch Inc.	■	■	■	■	■	■	■	■	■	■	■	■
(3) Barrel MicroMegas R&D:												
CAD work for PCB and mechanical structure	■	■	■									
Order at CERN and CIREA				■								
R&D on layout	■	■	■									
R&D on readout					■	■						
Test of prototype						■	■	■				
(4) Simulations												
Analytical resolution studies	■	■	■	■								
Fast simulations	■	■	■	■	■	■						
GEANT4 simulations	■	■	■	■	■	■	■	■	■	■	■	■

Figure 42: *Overview of the schedule concerning the main activities of both the forward and barrel R&D efforts.*

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